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Butanol / Gasoline Mercury CRADA Report

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16. Abstract (MAXIMUM 200 WORDS)

As an element in the Coast Guard's (CG) compliance strategy for decreasing greenhouse gases (GHG), and increasing the use of alternative fuels, the USCG Research & Development Center (RDC) tested a blend consisting of 16.1 percent biobutanol by volume (BU16), with regular E0 gasoline. BU16 is a renewable alternative gasoline fuel. The RDC tested BU16 on a USCG 38' Special Purpose Craft – Training Boat (SPC-TB) powered by twin Mercury 300 HP Verado engines at CG Training Center Yorktown, VA.

Butanol was obtained from Gevo Inc, currently the sole United States supplier, working through a local distributor who blended and delivered it. Fuel quality was monitored throughout the test. Before the operational test, Mercury Marine conducted materials testing to examine engine compatibility with BU16, bench testing to measure emissions, and on-water testing to assess engine performance.

Operational testing was conducted from 1 July 2013 to 31 July 2014. The SPC-TB underwent typical training missions and ran periodic baseline tests using E10 gasoline and BU16 for comparison. The RDC collected and analyzed engine performance data and crew observations of boat performance and maintenance. Details of the testing, and the conclusions and recommendations are included in the report.

17. Key Words	18. Distribution Statement
Biobutanol, isobutanol, BU16, alternative fuel, carbon footprint, emissions, greenhouse gas (GHG), Special Purpose Craft – Training Boat (SPC-TB), Tier II testing, Energy Independence and Security Act (EISA), Oak Ridge National Laboratory (ORNL), Mercury Marine, compatibility, Gevo	Distribution Statement A: Approved for Public Release; distribution is unlimited.

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EXECUTIVE SUMMARY

Federal laws and mandates issued in recent years have focused attention towards reducing energy use and greenhouse gas (GHG) emissions, and increasing the use of renewable energy sources. Two prominent examples are the Energy Independence and Security Act (EISA) of 2007, which sets requirements for reducing energy and increasing the use of alternative fuels, and Executive Order (EO) 13514, which requires agencies to establish reduction targets for GHG. To meet these requirements, the United States Coast Guard (USCG) has commissioned studies, with an overarching objective of reducing its carbon footprint through various approaches.

As part of this effort, the USCG Research and Development Center (RDC) initiated studies to examine alternative fuels, leading to the current Operational Testing Project. The first study addressed Alternative Fuel Options for Coast Guard (CG) boats, identifying options for replacing the currently used ten percent ethanol (E10) gasoline for outboards. The study identified a 16.1 percent mixture of biobutanol and gasoline (BU16) as the E10 alternative. This earlier work also suggests that biobutanol offers the Coast Guard a number of advantages, including:

- Biobutanol is a butanol that can be produced through processing of domestically grown crops, currently such as corn and sugar cane, and in the future other biomass, such as fast-growing grasses and agricultural waste products. This highlights its potential environmental benefit.
- Biobutanol is a liquid alcohol that can be used in gasoline engines and can be a direct substitute for ethanol in blended gasoline without any engine conversion or modification.
- Biobutanol is compatible with the current gasoline distribution infrastructure and can be blended at the refinery.
- Biobutanol would not require new or modified pipelines, blending facilities, storage tanks, or retail station pumps that Coast Guard sometimes uses for its fuel.
- Biobutanol is less affected than ethanol by problems associated with water absorption in the fuel, which can cause problems particularly in the marine environment.

A second study developed a plan to test BU16 in CG boats, assessing boat performance, and the modifications required to use the fuel. The third study (and current project) executed this test plan to quantify implementation issues, benefits and impacts of using the alternative fuel in CG boats under typical mission conditions (Operational Testing). This report addresses the results of the operational testing.

The RDC and Mercury Marine (Mercury), the manufacturer for the outboard engines used on the SPC-TB, entered into a Cooperative Research and Development Agreement (CRADA) to study the use of BU16. Mercury conducted materials testing to examine engine compatibility with BU16, and bench testing to determine emission characteristics. Operational testing took place over a full year, to experience most typical environmental conditions and operational activities at the unit. Testing took place on a 38' Special Purpose Craft – Training Boat (SPC-TB) operating out of USCG Training Center Yorktown, VA. Test data consisted of environmental data, engine/fuel system data, fuel chemistry, and crew observations. In addition, Oak Ridge National Laboratory (ORNL) provided expertise relating to the fuel specification, BU16.

The test team, SPC-TB coxswains and crewmembers perceived no performance difference and no effect on maintenance when operating on BU16 fuel, compared to E10, or when both fuels were mixed together.

Testing performed by Mercury determined that emissions from the test engines were equivalent whether operating on BU16 or E10. Mercury found no BU16 compatibility issues with the test engines. In addition, after testing for materials compatibility and visually examining engine components following bench testing, Mercury detected no difference between the effects of E10 and BU16.

BU16 is not in current commercial use, so its use as a test fuel raised logistical and economic challenges that would normally be resolved by market forces for a commercially available fuel. Two issues that need to be investigated further as commercial production increases and BU16 becomes commercially available are;

- Increasing percentage levels of butanol during extended storage noted during this study.
- Fuel distribution infrastructure materials compatibility.

Based on the testing in this study, BU16 is a suitable alternative fuel for the E10 currently used by the SPC-TB, within the environmental conditions experienced and for the test engines used in the study.

We recommend that the Coast Guard take some basic actions to position itself for the future availability of this fuel.

- Continue to monitor the commercial production capability of biobutanol producers as they bring their product to market.
- Once commercial availability has been established, consider adding biobutanol fuel capability as an added requirement for future outboard engine procurements.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF TABLES

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LIST OF ACRONYMS

AF	Alternative fuel
ASTM	American Society for Testing and Materials
BTL	Biomass-to-liquids
BU16	16 percent biobutanol/84 percent gasoline blend fuel
C	Celsius
CG	Coast Guard
CO	Carbon monoxide
CO2	Carbon dioxide
CNG	Compressed natural gas
CRADA	Cooperative Research and Development Agreement
DIW	Dead in the water
DOE	Department of Energy
E0	Ethanol-free gasoline
E10	10 percent ethanol gas/90 percent gasoline blend fuel
EISA	Energy Independence and Security Act
EO	Executive Order
EPA	Environmental Protection Agency
F	Fahrenheit
GHG	Greenhouse gas
GPH	Gallons per hour
GPS	Global Positioning System
HP	Horsepower
IMO	International Maritime Organization
KT	Knot
KW	Kilowatt
MFI	Multiport fuel injection
MSDS	Material Safety Data Sheet
NM	Nautical miles
NMEA	National Marine Electronics Association
ORNL	Oak Ridge National Laboratory
Prpm	Port RPM
RDC	Research and Development Center
R&D	Research and Development
RPM	Revolutions per minute
SAE	Society of Automotive Engineers
SOG	Speed over ground
Srpm	Starboard RPM
STBD	Starboard
TCTO	Time Compliance Technical Order
TRACEN	Training Center
USCG	United States Coast Guard
WX	Weather Station

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1 BACKGROUND

In recent years, the International Maritime Organization (IMO), Environmental Protection Agency (EPA), the United States (US) Congress, and the White House have established policies designed to reduce air pollutants, reduce carbon footprint, and encourage the use of alternative fuels. Some of these actions, particularly in the federal domain, influenced initiation of this project and are described below.

1.1 Federal Mandates and Greenhouse Gas Emissions

The Energy Independence and Security Act (EISA) of 2007 (P.L. 110-140, H.R. 6) aims to increase U.S. energy security, increase the use of biofuels, and improve vehicle fuel economy. Using 2005 as a baseline, EISA requires federal agencies to reduce facility energy consumption by 30 percent, reduce petroleum consumption by 20 percent, and increase alternative fuel consumption by 10 percent by 2015.

Executive Order (EO) 13514; Federal Leadership in Environmental, Energy, and Economic Performance (2009), requires agency-wide reduction goals for energy, water and waste. E.O. 13514 also requires agencies to establish reduction targets for direct greenhouse gas (GHG) emissions from sources that are owned or controlled by the Federal agency, defined as Scope 1 emissions. The Department of Homeland Security (DHS) Strategic Sustainability Performance Plan sets a 25% GHG Scope 1&2 reduction goal for the United States Coast Guard (USCG) by FY 2020 (relative to its FY 2008 baseline). An example of Scope 1 emissions are those from Coast Guard (CG) boats. To achieve this GHG reduction goal, DHS developed a high-level approach that includes short-, medium- and long-term initiatives. These activities build on existing efforts to reduce the energy intensity of its operations, increase the utilization of alternative fuels (AFs), and purchase renewable energy. The DHS plan identifies increased use of AFs in alternative fuel vehicles and flex-fuel vehicles. To support these goals, the CG has commissioned studies designed to research and test alternative fuels, with an eye towards greater accountability of fleet fuel usage, reduced greenhouse emissions and future cost savings.

1.2 Alternative Fuels

Alternative fuels are any fuels other than traditional petroleum-based gasoline or diesel. The alternative fuel tested in this project was a 16.1 percent by volume blend of biobutanol (isobutanol) in gasoline (BU16). This blend was determined by a prior Research & Development Center (RDC) study, described as Project 1 below. Biobutanol and petrobutanol have the same chemical properties, however biobutanol can be produced from various types of biomass. Currently, butanol is primarily used as an industrial solvent in products such as lacquers and enamels.

Butanol is a 4-carbon alcohol, which is also known as butyl alcohol, and can refer to any of the four isomeric alcohols of formula C_4H_9OH. Ethanol and isobutanol are both alcohols and have some similarities, such as containing fuel-bound oxygen, being polar molecules, and being fully miscible with gasoline on their own, and fully miscible as a mixture in gasoline blends. Like ethanol, biobutanol is a liquid alcohol fuel that can be used in today's gasoline-powered internal combustion engines. Butanol has a higher energy density than ethanol, but in gasoline blends with the same oxygen content, the energy density is approximately the same. This study compared E10 with BU16, which have approximately the same energy density, thus there is no expected fuel economy benefit.

One of the main differences between ethanol and isobutanol mixtures is their interaction with water. If the fuel mixtures are exposed to a sufficient amount of water to form an aqueous phase, either through absorption from humid air or through exposure to liquid water (exposure to rain, for example), ethanol preferentially goes to the aqueous phase. This significantly changes the fuel properties of the fuel remaining in the non-aqueous phase, particularly the octane number. In contrast, isobutanol primarily stays in the non-aqueous phase, allowing the aqueous phase to be removed from the fuel with minimal impact on fuel properties. This difference in the interactions with water is one of the reasons why isobutanol may be preferred in the marine environment, where fuel is continuously subject to exposure to water. Recent breakthroughs in biobutanol production technology, namely the discovery and development of genetically-modified microorganisms, have made it possible for biobutanol to begin to replace ethanol in large quantities. Biobutanol, isobutanol and butanol, are used synonymously in this report.

Engines running on biofuels emit carbon dioxide (CO_2), the primary constituent of greenhouse gas emissions. Fossil fuel use produces CO_2 from carbon that has been stored underground, producing a net CO_2 addition to the atmosphere. Because biofuels are derived from plants, which consume atmospheric CO_2 during their growth, the release of CO_2 when biofuels are burned effectively recycles atmospheric CO_2 that was previously absorbed from the atmosphere. The use of fossil fuels on the other hand, releases carbon that has been stored underground, generating a net CO_2 addition to the atmosphere. Biofuels still use fossil fuels such as coal and natural gas for their production, so they currently represent a small net atmospheric CO_2 source. Replacing traditional fuels with biofuels however, can reduce the carbon footprint. The RDC initiated several studies to examine alternative fuels, with two of the studies leading to the current Operational Testing Project. These studies are described below.

2 OVERVIEW OF THE OPERATIONAL TESTING PROJECT

The Operational Testing Project is the third in a series of RDC studies that examined the use of alternative fuels as potential substitutes for E10 gasoline. This report presents the results of testing an isobutanol-based alternative fuel.

2.1 Project 1: Alternative Fuel Study

The first RDC study addressed alternative fuel options for CG vessels, identifying alternative fuels, appropriate boat classes, and locations for testing. Liquid and gaseous alternative fuels, were evaluated and ranked, and a comprehensive initial list of eleven gasoline alternative fuels was developed from those listed on the Department of Energy's (DOE) Web site (http://www.afdc.energy.gov/afdc/) and fuels recommended by CG subject matter experts (SMEs). This list was reduced using four criteria:

1. Affordability.
2. Availability.
3. Safety.
4. Potential Carbon Footprint Reduction.

Using these criteria, the initial list was reduced to the following alternative fuels for further analysis:

1. Compressed natural gas (CNG).
2. Liquid Natural Gas (LNG).
3. Ethanol and ethanol mixtures.
4. Biobutanol.

5. Biomass-to-liquids (BTL).

2.1.1 Test Fuel

The above five candidates were evaluated against 25 attributes in a fuel evaluation matrix (6APPENDIX A), using E10 gasoline as a baseline fuel for comparison. The RDC, with sponsor and stakeholder input, selected a 16.1 percent blend of biobutanol with gasoline (BU16) as the test fuel. Gaseous alternative fuels (CNG and LNG) were eliminated due to low volumetric energy density, issues associated with locating fuel storage tanks, the costly and extensive modifications required to the fuel system and the engines, and the perceived risk associated with high pressure fuel. BTL was considered high risk because it was not readily available for test purposes, nor was there much experience with it in the transportation sector. The biobutanol used for the BU16 blend was made from a process currently under development by Gevo, Inc. No other suppliers for biobutanol are currently producing in the U.S.

2.1.2 Test Platform and Location

The RDC selected the 38' Special Purpose Craft – Training Boat (SPC-TB) with Mercury Marine (Mercury) outboard engines as the BU16 test platform (Figure 1), because Mercury engines are used on many CG boats. The RDC designated USCG Training Center (TRACEN) Yorktown, VA as the test unit for two reasons:

- Avoidance of operational impact on a USCG SAR or MLE mission unit, such as a small boat station; and
- availability of platforms for testing related to this project.

Unless otherwise specified, the term "SPC-TB" is used in this report to refer to the test boat, CG 38114, located at the TRACEN Yorktown. Table 1 shows the SPC-TB class characteristics.

Figure 1. 38' SPC-TB.

Table 1. SPC-TB class characteristics.

Operational Characteristics		Physical Characteristics	
Max Range @ Cruise Speed	260 NM[1]	LOA[2]	40’-9”
Max Speed	38 knots @ 5500 RPM[3]	Beam Overall (includes collar)	10’-8 3/4”
Cruise Speed	24 knots @ 4500 RPM	Operational Draft (DIW[4] with engines vertical)	3’-0 3/4”
Maximum Operating Distance from Shore	50 NM Range: 260 NM	Propulsion	Two Mercury Marine Verado 300 HP[5], 4-stroke outboard engines
Fuel Consumption @ 6000 RPM (both engines)	59.6 GPH[6]	Generator	11.5 KW[7]
Fuel Consumption @ 4500 RPM (both engines)	35.7 GPH	Generator engine	Westerbeke diesel generator
		Displacement (without crew)	17,563 pounds
		Fuel Tank Capacities	400 gallons: gas 28 gallons: diesel
		Number of Fuel Tanks	1 Gasoline 1 Diesel
		Crew/Student Capacity (seated)	Two crew, six students
		Deckhouse	Aluminum (5086 Grade)
		Hull	Aluminum (5086 Grade)

[1]nautical mile
[2]length overall
[3]revolutions per minute
[4]dead in the water
[5]horsepower
[6]gallons per hour
[7]kilowatt

2.1.3 Mercury Marine CRADA

The RDC signed a Cooperative Research and Development Agreement (CRADA) with Mercury on 12 January 2012 to provide technical assistance during the testing. CRADAs are authorized by the Federal Technology Transfer Act of 1986 (Public Law 99-502, codified at 15 U.S.C. 3710(a), as amended. A CRADA promotes the transfer of technology to the private sector for commercial use, as well as specified research or development efforts that are consistent with the missions of the federal laboratories that are party to the CRADA. The federal party or parties agree to share research resources with one or more non-federal parties. The federal laboratories can contribute all warranted and available resources except funds. Mercury provided technical input for the fuel selection and test plan, and performed materials testing, emissions testing and limited field testing.

2.1.4 Oak Ridge National Laboratory

The RDC established an interagency agreement with the DOE to obtain technical support from the Oak Ridge National Laboratory (ORNL) for the testing. ORNL provided:

- Guidance to RDC on the test fuel blend, including the “aggressive” BU16 blend;
- input and review of a protocol to assure fuel quality and compatibility during the tests; and
- review of fuel issues during operational testing.

2.2 Project 2: Test Plan Development

A second RDC study was conducted to develop a BU16 Test Plan (6APPENDIX B). In addition, a draft Time Compliance Change Order (TCTO) (6APPENDIX C) was prepared, which described planned changes to the SPC-TB to prepare for testing. Section 3.2 discusses the modifications made. The protocol developed for testing alternative fuels included four phases: materials, bench, field, and operational testing, as noted below.

- **Materials Testing** to determine the compatibly of the engine fuel system components and fuel-wetted parts with BU16. Mercury performed this testing and refers to it as fuel system bench testing in their report.
- **Bench Testing** to ensure the engines will operate satisfactorily on BU16 and to determine the need for engine adjustments. Mercury performed this testing in two parts, referred to as, (1) Dynamometer Evaluation (including emissions testing), and (2) Calibration Drivability Evaluation. The latter testing was performed on the water and with similar objectives to the Field Testing described below.
- **Field Testing** to ensure the entire fuel system (i.e., the fuel tank all the way to the engines) is compatible with the biobutanol blend, and to establish baselines on the normal fuel (E10) and the test fuel (BU16) for comparison purposes. This testing was accomplished by the RDC test team and TRACEN Yorktown personnel. For this project, field testing was an early phase of operational testing.
- **Operational Testing** to determine the feasibility of using BU16 in CG boats. This testing was accomplished by the test team and TRACEN Yorktown personnel.

2.3 Project 3: Operational Testing

The current RDC study carried the investigation of alternative fuels forward to the next phase, executing the test plan developed in the previous study. The objective of this phase was to identify and quantify any implementation issues, benefits and impacts of using BU16. Testing focused on operations, engine performance, engine maintenance, and crew health and safety, with the goal of identifying impacts that would exceed nominal operating parameters. In the long-term, the purpose of operational testing was to contribute to the CG's overall goal of achieving the carbon reduction mandate described earlier, by converting a portion of its boat fleet to a renewable fuel that might offer benefits not realized with current E10 use.

3 PREPARATIONS FOR OPERATIONAL TESTING

The following major activities were completed before operational testing began:

- Mercury materials, emissions, and bench testing.
- Installation of the data collection system on the SPC-TB.
- BU16 logistics.

3.1 Mercury Testing

Mercury determined that the performance of the Mercury Verado test engines when running on BU16 was equivalent, to performance when using E10 or ethanol free gasoline (E0). Mercury found no problems during their testing that would prevent the USCG from proceeding with the BU16 operational test. The subsections below present outcomes from Mercury testing. The full report of the Mercury testing is included in 6APPENDIX D.

3.1.1 Fuel System Bench Test

Mercury used four blends of fuel to investigate materials compatibility of the fuel system:

1. E0.
2. BU16.
3. BU16 (aggressive blend – described below).
4. 83.7 percent American Society for Testing and Materials (ASTM) D-471-79 Ref C fuel + 16 percent Butanol + .03 percent Tertiary Butyl Hydro-Peroxide.

A BU16 aggressive blend (fuel blend 3) was defined by ORNL to accelerate or magnify the expected harmful effects of the fuel on materials, enhancing the ability to detect materials incompatibility issues over the test duration. While there is no standardized aggressive blend for isobutanol, the blend for isobutanol was based on the standard aggressive blend for ethanol specified in Society of Automotive Engineers (SAE) standard J1681. The aggressive blend of Butanol included 0.099-percent deionized water, 5-ppm sodium, 25-ppm sulfuric acid, and 75-ppm isobutyric acid. The aggressive isobutanol formulation was blended with E0 gasoline at 16.1percent by volume.

Mercury concluded that performance of the components listed below passed post-evaluation examination after testing at an elevated temperature of 60 degrees C for 30 days.

1. Fuel water separator filter.
2. Fuel hoses.
3. Fuel injectors.
4. Vent canister.
5. Fuel supply module.

In summary:

- All fuel system components performed within specification after exposure to butanol test fuels as designed by test procedure and engine requirements.
- Changes in elastomer material properties were observed equally in baseline and butanol fuels.

3.1.2 Dynamometer Evaluation

Mercury used three fuels in the running engine testing, intended to represent typical pump-grade fuels that could be commonly available to the general consumer, or commonly used reference-grade fuel to establish a baseline:

1. BU16. Since the Mercury test engines have a premium fuel recommendation, the butanol fuel was blended at a target of 90-octane.
2. Emissions reference fuel (EPA Tier II EEE fuel).
3. Pump-grade premium E10 gasoline.

From this testing, Mercury concluded that power output was slightly higher when using butanol fuel. Most of the difference in power can be attributed to higher airflow, due to better intake air cooling (thus higher density) from the alcohol fuel. Leaner operation compared to E0 was also likely a factor.

3.1.3 Boat Drivability Evaluation

Following dynamometer testing, Mercury installed a 300 HP Verado test engine on a 21-foot Boston Whaler to perform on-water drivability testing. The objective of this testing was to detect differences produced by the leaner fuel mix produced by BU16 relative to E0. The test boat performed maneuvers designed to simulate demanding real-world usage, including starting (cold and warm), transient performance (hard acceleration, rapid deceleration, etc.), shifting performance/stability, and extended idle with drive-away.

Mercury found no notable differences in run quality between the E0 and BU16 fuels that it tested. The BU16 fuel performed as well as or better than the E0 baseline fuel. Mercury also detected no issues on any of the maneuvers tested. In cold starting tests, Mercury determined that the engine started slightly sooner with BU16 than with E0, and as a result did not have as much speed overshoot, and settled down to normal idle speed slightly faster. In summary, Mercury concluded that the Verado engine had acceptable drivability performance on BU16.

3.1.4 Emissions Comparison

Mercury measured exhaust emissions, following the EPA 5-mode, steady state test, with Mode 1 being rated speed/full load and the subsequent mode points reducing in speed and load to Mode 5, which is idle. Fuels used in this testing were E0, E10 and BU16. Mercury determined the following when comparing the E0 reference fuel to both E10 and BU16:

- Hydrocarbon (HC) and carbon monoxide (CO) emissions are lower with oxygenated fuel. The open-loop Mercury Verado engines run leaner with oxygenated fuel, and generate lower HC and CO emissions.
- Emissions of oxides of Nitrogen (NOx) are higher with oxygenated fuel. NOx generation is a function of the time spent at high temperature/pressure in the combustion chamber. The engines run leaner and hotter with oxygenated fuel, which increases in-cylinder temperatures and thus generates higher NOx emissions.

3.2 Modifications to the SPC-TB

3.2.1 Data Collection System

After the initial installation of a National Marine Electronics Association (NMEA) 2000 network, the test team added a NMEA 2000-compatible Global Positioning System/Weather (GPS/WX) sensor (PB200), and a computer specifically configured to record the NMEA 2000 data. The PB200 is an integrated collection of sensors used to record environmental data (temperature, wind speed, etc.) as well as GPS position, course, speed, and boat roll and pitch. The computer, made by Chetco Inc., ran a software package called vDash®, and featured a special input port to connect to the NMEA 2000 network. The computer was connected to a wireless router, allowing the test team to remotely monitor the network. Mercury provided an adapter/gateway that converted the Mercury proprietary data to NMEA 2000 data. This finalized the data collection system installation in July 2013, as shown in Figure 2, to begin operational testing.

Once the data collection system was up and running, three other issues surfaced.

- If the Chetco computer was powered down by opening the circuit breaker, rather than via the computer operating system, it froze upon startup. To restart the system, the test engineer remotely walked the boat crewman through the required steps.

- Interaction between the vDash software and the Windows operating system sometimes caused the NMEA data coming across the serial port to be interpreted as a hardware install request, automatically installing a mouse driver on the port. The data flowing through the port caused this "virtual mouse" to randomly click over the screen, which shut down the data collection system and ended testing. Although the test engineer was able to log on remotely to restart the system, this did not prevent occasional reoccurrences.
- During the programing of the NMEA recorder, the test team noted that much of the data passing through the Mercury gateway was being lost. The test team determined that the gateway was passing a massive amount of proprietary Mercury data onto the network, slowing it down to the point where it dropped data packets. Chetco resolved this issue by adjusting the vDash code to ignore (pre-filter) the proprietary data, and by adjusting the sample rates for other inputs, e.g. air temperature, to greatly reduce the amount of data over the network.

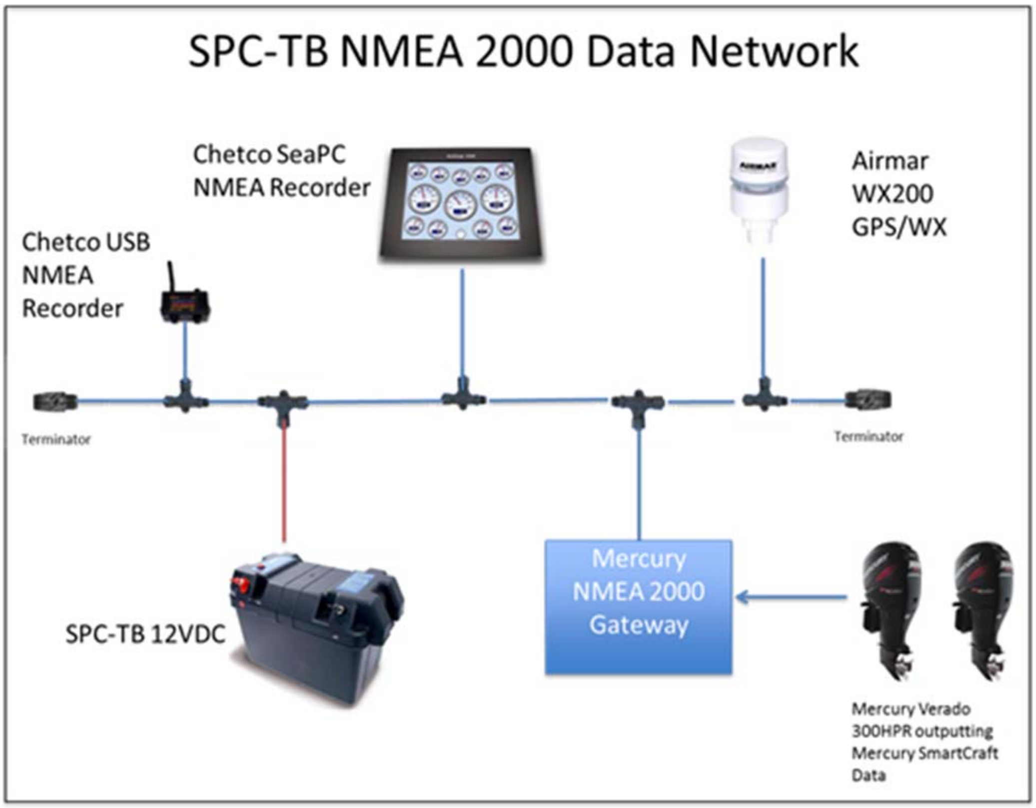

Figure 2. NMEA 2000 network system.

3.3 SPC-TB Fuel System

Experts generally believe that the material compatibility challenges with isobutanol are less severe than those posed by ethanol for engine fuel systems designed for gasoline, such as the SPC-TB. Therefore, BU16 was expected to have fewer materials compatibility issues than E10 (Kass et al. 2013, Kass et al. 2014, Kass et al. 2014). A list of wetted fuel parts was prepared to guide a materials audit that was conducted prior to the current project. In addition, Mercury testing examined material compatibility by exposing fuel system parts to the aggressive fuel blend described in Section 3.1.1. Mercury concluded that all components maintained their system and component function regardless of changes to material properties, and materials were not affected

differently by E10 and BU16. Based on this result, no components needed replacing due to material compatibility with BU16. Prior to the start of testing, Mercury and the test team replaced the following engine components due to previous exposure to E10. The new replacement parts ensured a known state from which to evaluate any observed differences at the end of testing.

- Intake manifold and injectors.
- Spark plugs.
- Fuel supply module.
- High pressure fuel filter.
- Fuel lines.
- Engine oil and filter.

3.3.1 Test Preparation Costs

Table 2 identifies the costs to prepare the SPC-TB for operational testing. These costs include parts for installing the data collection system described above. Labor costs by TRACEN Yorktown and the test team are not included.

Table 2. BU16 test preparation costs.

ITEM	COST
NMEA 2000 network parts	$180
Mercury N2K Converter (provided by Mercury)	$600
Miscellaneous installation hardware	$325
Chetco SeaPC data computer	$3,250
Chetco USB NMEA recorder	$595
Airmar GPS/WX station	$1,150
TOTAL	**$6,100**

3.4 Test Fuel Logistics

Biobutanol for the test fuel blend was provided by the only current U.S. supplier, Gevo, Inc. Gevo contracted with Domestic Fuels (Domestic), a local fuel supplier in the Yorktown, VA area to blend and deliver the BU16. On 23 May 2013, Domestic mixed the biobutanol with E0 summer gasoline to make 10,000 gallons of BU16, to be stored in a tank at Domestic. Domestic delivered the fuel on demand to TRACEN Yorktown by tank truck. Upon arrival, the fuel was pumped into a trailerable 500 gallon storage tank. USCG personnel pumped the BU16 directly from the trailerable tank into the boat fuel tank as needed. The fuel quality was monitored via fuel sample analyses performed by both the RDC and the fuel supplier (Gevo) through independent testing laboratories. Section 4.5 describes fuel sample analysis and results.

4 OPERATIONAL TESTING

Operational testing began on 1 July 2013 and concluded on 31 July 2014, after 460 underway hours, and 2,937 gallons of BU16 used on the SPC-TB. During this testing, the SPC-TB performed typical duties, such as coxswain training and made designated test runs to generate acceptable baseline data using regular E10 gasoline and BU16. BU16 testing focused on operations, engine performance, engine maintenance, and crew health and safety, with the goal of experiencing no impacts that would be considered worse than the status quo in these primary areas.

On 9 September 2014, the test team and technicians from Mercury met at TRACEN Yorktown to take final actions on the test boat. The technicians exchanged out the components listed in Section 3.3 with new parts, and shipped the old parts to Mercury facilities for examination.. After the engines demonstrated to be running properly, the test team de-installed all test equipment, returning the SPC-TB to its pre-test condition.

4.1 Field Testing

For the first phase of operational testing, the test team conducted field testing at TRACEN Yorktown from 1 July to 31 July 2014, running baseline tests and inspecting the boat during and after operation to check for potential problems. After configuring the engines and data collection system, and working out residual setup issues, the test team adopted the following standard protocol to accomplish field and baseline testing on the SPC-TB.

1. A prolonged warm-up at idle (~1 hour) at the pier.
2. Slow-cruise < 10 KTS (minimum 1 hour).
3. Fast-cruise ~ 25 KTS (minimum 1 hour).
4. Wide-open throttle (minimum 1 hour).

The SPC-TB performed well using BU16 during the initial test, and no problems were detected. Additional field baseline tests were performed throughout the year-long operational test period (see Table 3) to capture the most usable data for comparison between E10 and BU16.

Table 3. SPC-TB baseline tests.

Test Week	BU-16	E-10
26 JUN 2013	✓	✓
28 AUG 2013	✓	
24 SEP 2013	✓	
28 OCT 2013	✓	
2 DEC 2013	✓	
13 JAN 2014	✓	
25 FEB 2014	✓	✓
14 MAY 2014	✓	
18 JUN 2014	✓	✓
22 JUL 2014	✓	✓✓ (2)

4.2 Fuel Effect on Boat Performance

Engine performance characteristics were assessed by monitoring the boat speed over ground (SOG), port and starboard (STBD) engine RPM, and fuel consumption in gallons per hour (GPH). Multiple operational field tests were carried out using each fuel (E10 and BU16) over the test period. During the tests, data elements (including the desired engine performance data) were recorded to a Windows-based Chetco computer. These binary data files were then parsed using the vDash software to produce spreadsheets containing the desired parameters. The data files were analyzed and filtered to only include reasonably long sample durations for each RPM range (1 thru 4 above). These samples were chosen from periods where port and STBD engine RPMs were synchronized and stable. Figure 3 shows an example of the chosen segments (in four vertical color bands). Figure 4 displays the resulting sample segments.

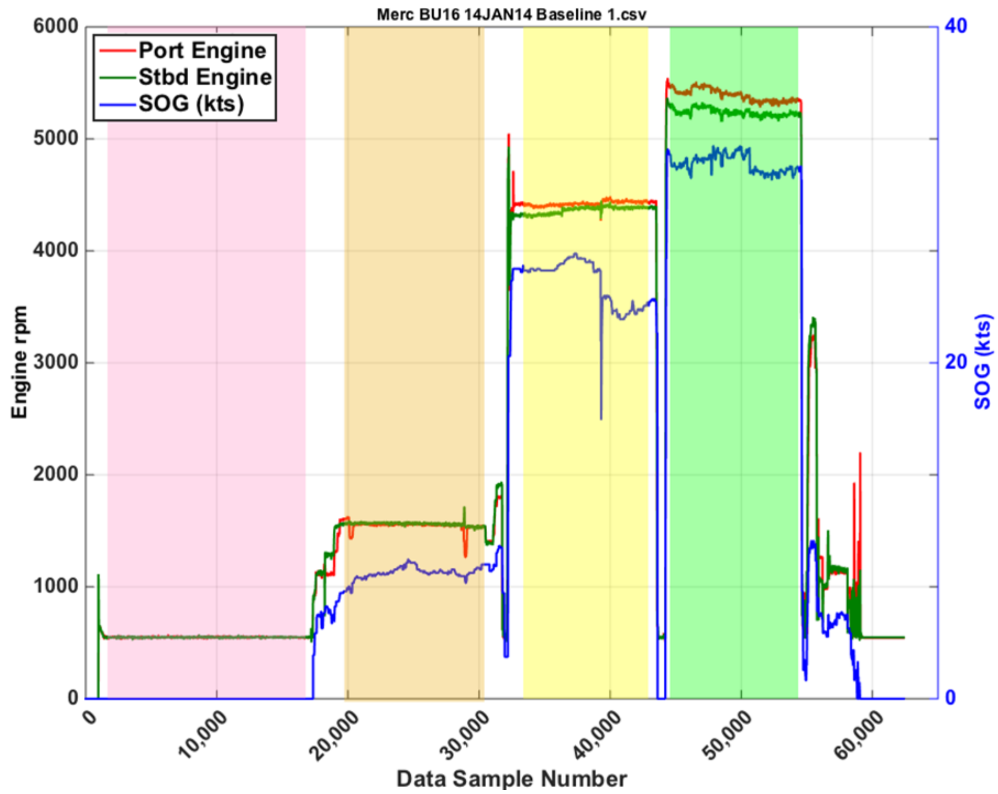

Figure 3. USCG data from Mercury engines showing example of four data segments.

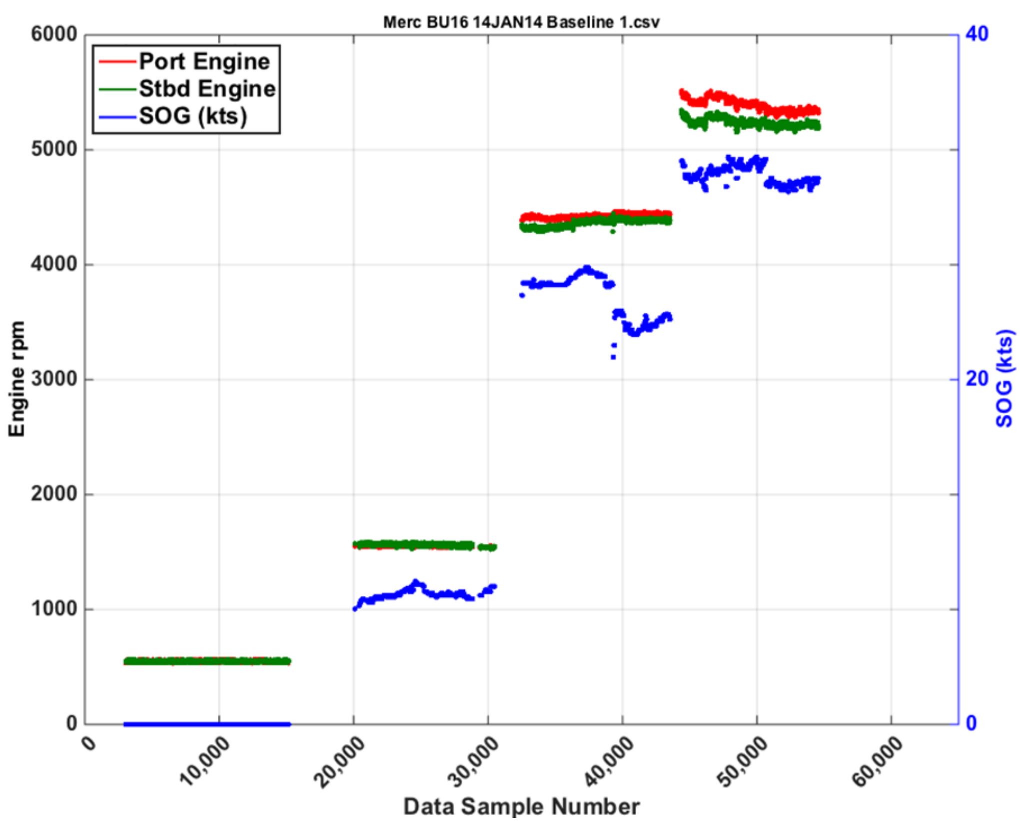

Figure 4. USCG data from Mercury engines showing only the data selected segments.

The test team selected the data segments in the above manner due to the operational nature of the testing; the tests were conducted in the normal operating area, which included an active shipping channel. The coxswains therefore had to make course and speed changes to avoid vessel traffic, especially during the wide-open throttle tests. Once the desired data segments were identified, each segment was passed through a 3σ filter to remove data outliers in the segment.[1] The data in each segment were then averaged to produce single data points of RPM, speed, and fuel flow for that segment. Table 4 shows the number of data segments for the desired RPM range, as well as the total number of samples recorded for all of these segments.

Table 4. List of data segments and number of samples.

	E10		BU16	
RPM Range	Data Segments	Total Samples	Data Segments	Total Samples
IDLE	5	52351	5	54957
SLOW-CRUISE	4	40584	4	28953
FAST-CRUISE	5	37847	5	49944
WIDE-OPEN THROTTLE	5	45965	5	86713

The averaged engine speed (RPM) versus fuel flow rate (GPH) points are shown in Figure 5, along with a reference line to compare with existing data. Since Mercury has not performed fuel consumption testing on the SPC-TB, the reference line represents data from SPC-TB testing performed by Metal Shark, the boat manufacturer, using 300 HP Mercury Verado engines. As the graph shows, the data collected during the operational tests agrees well with Metal Shark's testing.

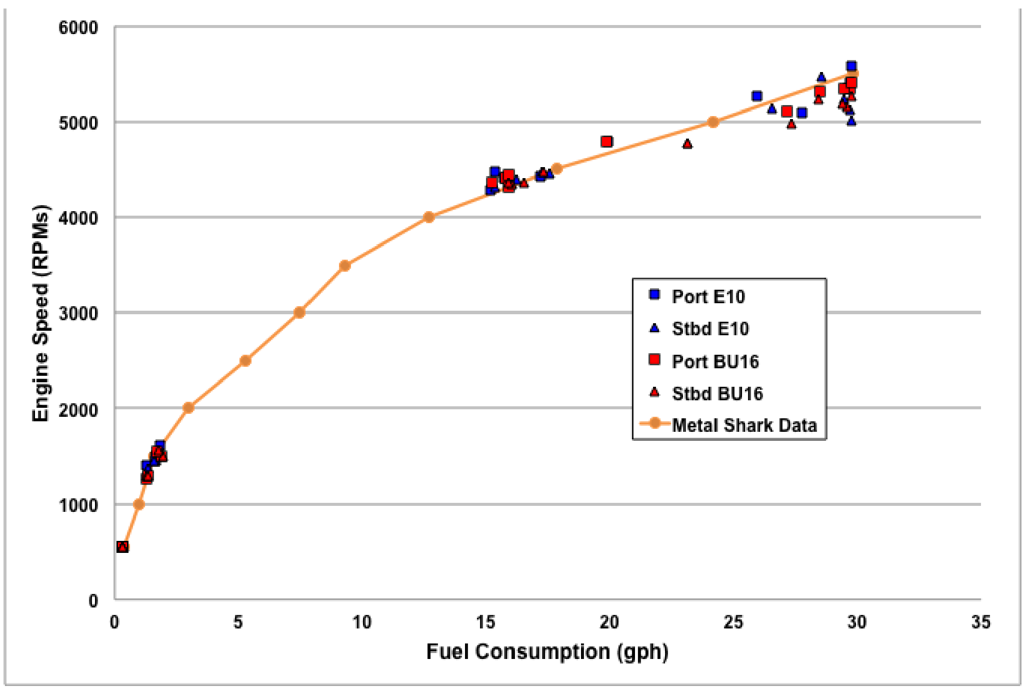

Figure 5. Mercury engine speed vs. fuel consumption.

[1] For each data vector, the mean and standard deviation was calculated for each segment (when the data was relatively constant). Any data point that was more than 3 standard deviations from the mean was deleted. This was necessary to remove data points that would improperly skew the results. Each data vector was filtered independently to remove outliers - although if an outlier was found in any of the 3 data vectors, that time sample was deleted for all 3 data vectors, to maintain time alignment between the vectors.

The fuel consumption comparison shows that boat performance will be similar for both BU16 and E10. The variances between the two engines are greater than the variances between the two fuels which is seen in the fuel consumption vs. engine speed graph.

4.3 Fuel Effect on Engine Maintenance and Service Life

The test team and boat crews noted no impact from BU16 on the maintenance required for the Mercury engines or the SPC-TB during the operational testing.

4.4 Emissions

Mercury performed engine exhaust emissions testing in conjunction with their bench testing, comparing the E0 reference fuel to both E10 and BU16. Mercury concluded that:

- Hydrocarbon (HC) and carbon monoxide (CO) emissions are lower with oxygenated fuel. The open-loop Mercury Verado engines run leaner with oxygenated fuel, and generate lower HC and CO emissions.
- Emissions of oxides of Nitrogen (NOx) are higher with oxygenated fuel. NOx generation is a function of the time spent at high temperature/pressure in the combustion chamber. The engines run leaner and hotter with oxygenated fuel, which increases in-cylinder temperatures and thus generates higher NOx emissions.

4.5 Fuel Quality

Fuel samples were collected by the RDC and Gevo/Domestic for analysis by independent testing laboratories. Gevo was required to provide the fuel at 16.1% biobutanol (isobutanol) blended with 87 octane regular unleaded gasoline (E0). BU 16 is a developmental alternative fuel, and at the beginning of the test, there was no approved ASTM specification for the butanol component that would be mixed with the gasoline. The RDC participated in an ASTM technical working group that developed the butanol specification (ASTM D7862), which was vetted and published in August 2013. The blended fuel (BU16) used in the operational test was mixed prior to the specification approval, but the butanol used in the blend was in compliance with the specification.

During the test period, BU16 was compared against ASTM-D4814, which is an approved standard for automotive fuels for ground vehicles equipped with spark-ignition engines and includes blends with oxygenates. Comparing the test results to this standard provided assurance that the fuel was in close compliance with a specification suitable for spark-ignition engine fuels, and theoretically should result in satisfactory operation. Testing also allowed trends in the test parameters to be identified over the course of the test.

Fuel quality issues did occur during testing, and are discussed below, however those issues did not halt testing, or affect boat operation. Table 5 provides the results of the fuel analyses made on the initial 10,000 gallon batch of fuel, and Table 6 provides the results of analyses conducted after the fuel was reblended to address high butanol levels as discussed in Section 5.1.4. The tables also provide a normal test result for regular gasoline (E0) for comparison.

Table 5. BU16 test results (original fuel batch).

Original Fuel Batch

Delivery Date >>			6/19/13	7/23/13	8/16/13	10/18/13	11/8/13	11/12/13	1/24/14	3/5/14
Gallons Delivered >>			750	446.7	425	450		400.1	414	449
Sampled by >>			GEVO	RDC	RDC	RDC	RDC	RDC	RDC	RDC
Sampled From >>			DST	DDT	DDT	DDT	DST	DDT	DDT	DDT
Testing Lab >>			Intertek	Southwest	Southwest	Southwest	Southwest	Southwest	Southwest	Southwest
Oxygenates and Total Oxygen	Regular Gasoline									
Methanol	(2)	Vol. %	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Ethanol	(2)	Vol. %	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Iso-Propanol	(2)	Vol. %	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
n-Propanol	(2)	Vol. %	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
t-Butanol	(2)	Vol. %	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
n-Butanol	(2)	Vol. %	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Iso-Butanol (16.1 (+/- 0.268%)	(2)	Vol. %	15.99	17.50	17.79	18.47	18.68	18.67	19.81	20.22
sec-Butanol	(2)	Vol. %	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
MTBE	(2)	Vol. %	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
ETBE	(2)	Vol. %	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
DIPE	(2)	Vol. %	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
TAME	(2)	Vol. %	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
t-Pentanol	(2)	Vol. %	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Oxygenates	(2)	Vol. %	15.99	17.50	17.79	18.47	18.68	18.67	19.81	20.22
Total Oxygen	3.7 % (Ethanol)(3)	Wt. %	3.70	2.74	4.08	4.22	4.24	4.24	4.46	4.62
(Vapor Pressure) RVP	(7-15 psi) (4)	psi	NT	6.67	6.77	6.38	5.32	5.30	4.46	4.04
(Vapor Pressure) DVPE		psi	NT	5.64	6.63	6.25	5.17	5.16	4.31	3.88
(Copper Strip Test) Corrosion	1-4 (5)	rating	NT	1A	1A	1A	1A	1A	1A	1A
(Copper Strip Test) Duration	Test parameters	hours	NT	3	3	3	3	3	3	3
(Copper Strip Test) Temp.	Test parameters	° C	NT	50	50	50	50	50	50	50
Heat of Combustion/Gross	20,000	BTU/lb	NT	NT	18874	NT	NT	NT	18788	NT
Heat of Combustion/Gross	46.52	MJ/kg	NT	NT	43.900	NT	NT	NT	43.700	NT
Heat of Combustion/Gross	11,300	cal/g	NT	NT	10485.3	NT	NT	NT	10437.5	NT
Heat of Combustion/Net		BTU/lb	NT	NT	17644	NT	NT	NT	17578	NT
Heat of Combustion/Net		MJ/kg	NT	NT	41.039	NT	NT	NT	40.888	NT
Heat of Combustion/Net		cal/g	NT	NT	9801.9	NT	NT	NT	9765.8	NT
Research Octane Number (RON)	(6)		NT	95.5	95.4	94.7	95.7	95.6	95.4	96.3
Motor Octane Number (MON)	(6)		NT	85.0	85.1	83.7	84.9	84.9	84.7	85.5
AKI (RON+MON)/2	87,89, or 91-94 (6)			90.3	90.3	89.2	90.3	90.25	90.05	90.9
Unwashed Gum		mg/100 mL	NT	9.0	48.0	536	12	10.5	13	14
Washed Gum	5 (Maximum)(7)	mg/100 mL	NT	1.0	6.0	13.0	2.5	2.5	5.0	<0.5
API Gravity	59.97		NT	55.5	55.1	54.5	53.1	53	51.5	50.6
Specific Gravity	0.739		NT	0.7568	0.7582	0.7608	0.7664	0.7669	0.7732	0.7769
Density at 15°C	710-770	g/L	NT	756.5	757.9	760.6	766.2	766.7	772.9	776.6
V/L Ratio	(97- 176)(8)	Temp. (°F)	NT	154.6	155.5	155.9	165.9	167	>176	>176
Oxidation Stability/Run Time	240 (Minimum)	minutes	NT	1440	1440	1440	1440	1440	1440	1440
Oxidation Stability/Break Pt.		yes/no	NT	No	No	No	Yes	Yes	Break	Break
Oxidation Stability/Break Pt.		minutes	NT	N/A	N/A	N/A	909	908	937	868
Water Content	(9)	ppm/mass %	NT	1539	2783	2835	2512	2524	2593	2319
Sulfur Content	0.0080% (Maximum) (10)	Wt. %	?	NT	0.0035	NT	NT	NT	0.0032	NT
Corrosion Silver Strip	0-4 (11)	rating	?	0	0	0	0	0	0	0
Test	**Limits**	**Units**	NT = not tested		DST = Domestic storage tank			DDT = Domestic delivery truck		

Notes: 1. Values in red represent out of spec test results

2. Regular gasoline can contain a number of different of oxygenates as listed. 10% Ethanol or less is the most common. The oxygenate test results (Less that 0.1% for all except isobuatnol) show isobuatnol is the primary oxygenate.

3. Maximum approved Oxygen concentration approved by EPA with 10 % Ethanol as oxygenate.

4. Normal Range of Vapor Pressure - Varies with the seasons - Lower vapor pressure prevents vapor lock and hot fuel handling problems but can make for hard starting. High values for better cold start performance.

5. Reported on scale of 1-4 with one being the best. Max. 1A = Freshly polished. 1B= Slight tarnish. 4 = worst, severe corrosion. Appears as blackened test coupon.

6. RON always greater than MON and difference indicates sensitivity of gasoline to operating condition changes. The larger the difference the more sensitive. Antiknock Index (AKI) is what is usually posed on pump. AKI is (RON+MON)/2. AKIs vary 87 for regular, 89 for midgrade and 91-94 for premium.

7. Impact of Solvent washed Gums on malfunctions of modern engines is not well established and the current specification limit is historic rather that result of recent correlative study.

8. Gasolines with higher values provide better protection against vapor lock and hot fuel handling problems.

9. Water in solution operates as an inert diluent and will be vaporized in the combustion process. Gasoline blends with low molecular alcohols can dissolve about 0.1 %(1000 ppm) to 0.7 % (7000 ppm) mass percent water under normal conditions.

10. Maximum Sulfur for unleaded gasoline.

11. Reported on scale of 0- 4 . 0= no tarnish, identical to a freshly polished strip, but may have some very light loss of luster.

Table 6. BU16 test results (reblended fuel).

			Reblended Fuel						
Delivery Date >>			4/25/14	5/15/14	5/21/14	6/5/14	6/24/14	7/3/14	7/3/14
Gallons Delivered >>			427.2			384.3			442.7
Sampled by >>			RDC	RDC	GEVO	RDC	GEVO	GEVO	RDC
Sampled From >>			DDT	DDT	YTT	YTT	DST	DDT	DDT
Testing Lab >>			Southwest	Southwest	Intertek	Southwest	Intertek	Intertek	Southwest
Oxygenates and Total Oxygen	Regular Gasoline								
Methanol	(2)	Vol. %	<0.1	NT	<0.1	<0.1	<0.2	<0.1	<0.1
Ethanol	(2)	Vol. %	<0.1	NT	<0.1	<0.1	0.28	<0.1	<0.1
Iso-Propanol	(2)	Vol. %	<0.1	NT	<0.1	<0.1	<0.2	<0.1	<0.1
n-Propanol	(2)	Vol. %	<0.1	NT	<0.1	<0.1	<0.2	<0.1	<0.1
t-Butanol	(2)	Vol. %	<0.1	NT	<0.1	<0.1	<0.2	<0.1	<0.1
n-Butanol	(2)	Vol. %	<0.1	NT	<0.1	<0.1	<0.2	<0.1	<0.1
Iso-Butanol (16.1 (+/- 0.268%)	(2)	Vol. %	24.35	16.86	16.69	21.23	15.27	18.57	20.46
sec-Butanol	(2)	Vol. %	<0.1	NT	<0.1	<0.1	<0.2	<0.1	<0.1
MTBE	(2)	Vol. %	<0.1	NT	<0.1	<0.1	<0.2	<0.1	<0.1
ETBE	(2)	Vol. %	<0.1	NT	<0.1	<0.1	<0.2	<0.1	<0.1
DIPE	(2)	Vol. %	<0.1	NT	<0.1	<0.1	<0.2	<0.1	<0.1
TAME	(2)	Vol. %	<0.1	NT	<0.1	<0.1	<0.2	<0.1	<0.1
t-Pentanol	(2)	Vol. %	<0.1	NT	<0.1	NT	<0.2	<0.1	<0.1
Oxygenates	(2)	Vol. %	24.35	NT	16.69	21.23	15.6	18.57	20.46
Total Oxygen	3.7 % (Ethanol)(3)	Wt. %	5.40	NT	3.8	4.99	3.6	4.2	4.59
(Vapor Pressure) RVP	(7-15 psi) (4)	psi	3.26	5.22	NT	3.07	NT	NT	4.38
(Vapor Pressure) DVPE		psi	3.09	5.07	NT	2.9	NT	NT	4.22
(Copper Strip Test) Corrosion	1-4 (5)	rating	1A	NT	NT	1A	NT	NT	1A
(Copper Strip Test) Duration	Test parameters	hours	3	NT	NT	3	NT	NT	3
(Copper Strip Test) Temp.	Test parameters	° C	50	NT	NT	50	NT	NT	50
Heat of Combustion/Gross	20,000	BTU/lb	18556	NT	NT	NT	NT	NT	18786
Heat of Combustion/Gross	46.52	MJ/kg	43.161	NT	NT	NT	NT	NT	43.696
Heat of Combustion/Gross	11,300	cal/g	10308.9	NT	NT	NT	NT	NT	10436.7
Heat of Combustion/Net		BTU/lb	17374	NT	NT	NT	NT	NT	17594
Heat of Combustion/Net		MJ/kg	40.412	NT	NT	NT	NT	NT	40.924
Heat of Combustion/Net		cal/g	9652.2	NT	NT	NT	NT	NT	9774.4
Research Octane Number (RON)	(6)		96.4	NT	NT	97	NT	NT	97.1
Motor Octane Number (MON)	(6)		85.4	NT	NT	84.9	NT	NT	86.1
AKI (RON+MON)/2	87,89, or 91-94 (6)		90.9	NT	NT	90.95	NT	NT	91.6
Unwashed Gum		mg/100 mL	13.5	29	NT	16	NT	NT	14.5
Washed Gum	5 (Maximum)(7)	mg/100 mL	4.0	5	NT	3.5	NT	NT	4.0
API Gravity	59.97		49.0	52.7	NT	48.4	NT	NT	51.1
Specific Gravity	0.739		0.7840	0.7682	NT	0.7865	NT	NT	0.7749
Density at 15°C	710-770	g/L	783.7	767.9	NT	786.2	NT	NT	774.6
V/L Ratio	(97- 176)(8)	Temp. (°F)	>176	NT	NT	>176	NT	NT	>176
Oxidation Stability/Run Time	240 (Minimum)	minutes	1440	NT	NT	1440	NT	NT	1440
Oxidation Stability/Break Pt.		yes/no	Break	Yes	NT	Break	NT	NT	Break
Oxidation Stability/Break Pt.		minutes	792	665	NT	905	NT	NT	905
Water Content	(9)	ppm/mass %	2862	NT	NT	3105	NT	NT	1906
Sulfur Content	0.0080% (Maximum) (10)	Wt. %	0.0032	NT	NT	NT	NT	NT	0.0033
Corrosion Silver Strip	0-4 (11)	rating	0	NT	NT	0	NT	NT	0
Test	**Limits**	**Units**	NT = not tested				DST = Domestic storage tank		
			DDT = Domestic delivery truck				YTT = Yorktown trailerable tank		

Notes: 1. Values in red represent out of spec test results
2. Regular gasoline can contain a number of different of oxygenates as listed. 10% Ethanol or less is the most common. The oxygenate test results (Less that 0.1% for all except isobuatnol) show isobuatnol is the primary oxygenate.
3. Maximum approved Oxygen concentration approved by EPA with 10 % Ethanol as oxygenate.
4. Normal Range of Vapor Pressure - Varies with the seasons - Lower vapor pressure prevents vapor lock and hot fuel handling problems but can make for hard starting. High values for better cold start performance.
5. Reported on scale of 1-4 with one being the best. Max. 1A = Freshly polished. 1B= Slight tarnish. 4 = worst, severe corrosion. Appears as blackened test coupon.
6. RON always greater than MON and difference indicates sensitivity of gasoline to operating condition changes. The larger the difference the more sensitive. Antiknock Index (AKI) is what is usually posed on pump. AKI is (RON+MON)/2. AKIs vary 87 for regular, 89 for midgrade and 91-94 for premium.
7. Impact of Solvent washed Gums on malfunctions of modern engines is not well established and the current specification limit is historic rather that result of recent correlative study.
8. Gasolines with higher values provide better protection against vapor lock and hot fuel handling problems.
9. Water in solution operates as an inert diluent and will be vaporized in the combustion process. Gasoline blends with low molecular alcohols can dissolve about 0.1 %(1000 ppm) to 0.7 % (7000 ppm) mass percent water under normal conditions.
10. Maximum Sulfur for unleaded gasoline.
11. Reported on scale of 0- 4 . 0= no tarnish, identical to a freshly polished strip, but may have some very light loss of luster.

The RDC required up to 18,600 gallons of BU16 (for the RB-S and for another test boat that is reported separately), based on projected fuel consumption from TRACEN Yorktown estimates. Domestic Fuels blended, stored, and delivered the BU16 fuel to TRACEN Yorktown. Based on the fuel requirement, Domestic dedicated a 10,000 gallon storage tank at their facility and a fuel delivery truck specifically for use on this project. Actual test boat running time was much less than planned, and consumed just under than 5,000 gallons of BU16 for the RB-S and the other test boat combined. Eleven BU16 deliveries were made from June 2013 through July of 2014, totaling 4,927.8 gallons. Table 7 provides the delivery dates and quantities delivered.

Table 7. BU16 deliveries.

Delivery Date >>	6/19/13	7/23/13	8/16/13	10/18/13	11/12/13	1/24/14	3/5/14	4/25/14	4/30/14	6/5/14	7/3/14
Gallons Delivered>>	750	446.7	425	450	400.1	414	449	427.2	338.8	384.3	442.7

4.5.1 Biobutanol Percentage

Deliveries were made from the initial 10,000 gallon batch of BU16 over the course of the testing. As the fuel aged during the test period, the biobutanol percentage in the delivered fuel varied. The test team considered butanol levels within 1% of the contract requirement of 16.1% to be acceptable for test purposes. By the second fuel delivery on 23 July 2013, the butanol level had risen above the acceptable range (17.5%), and continued to increase to a maximum of 20%, as measured on 5 March 2014. Gevo concluded that the increase in butanol level resulted from vaporization of some of the more volatile compounds in the blend, due to the extended length of time the blended fuel was held in the storage tank. Figure 6 provides biobutanol test results for the test period.

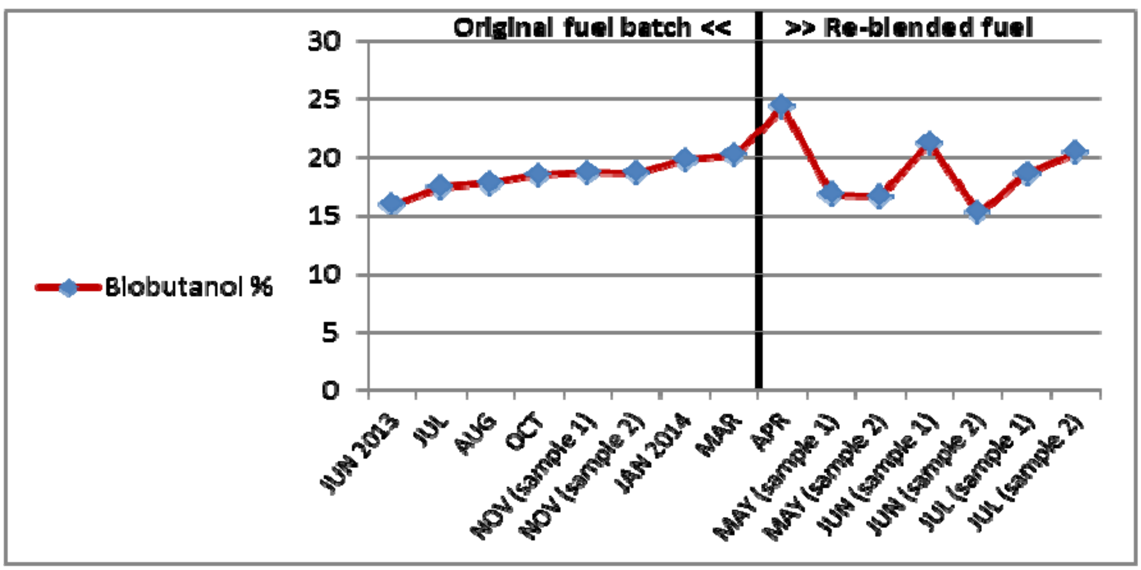

Figure 6. Biobutanol test results.

In January 2014, the test team, in conjunction with ORNL, discussed the rising isobutanol percentage and ways to manage it. Gevo proposed the following steps to re-blend the stored fuel back to 16.1 percent butanol:

1. Test the storage tank to measure the current butanol percentage and calculate a re-blend formula.
2. Retrieve the existing fuel located at TRACEN Yorktown in the tanks of the test boat and the trailerable tank.

3. Purchase eight 55 gallon drums of E0, to produce 2,000 gallons of BU16, based on the existing percentage in the storage tank (the RDC had projected 2,000 gallons was required to complete remaining operational testing).
4. Generate 500-gallon batches of 16 percent isobutanol fuel by blending 100 gallons of E0 with 400 gallons of current fuel for each required delivery (per the formula calculated in item 1 above).

Domestic used the above procedure to re-blend BU16 fuel on 24 April 2014 for the final four deliveries to lower the butanol percentage. Three subsequent test results indicated an excessive level of butanol in the blend; however, the test team determined that the high readings were the result of improper sample collection techniques during the delivery, and not higher butanol levels. Sampling errors consisted of collecting the sample prior to flushing the tanker delivery line that had contained BU16 from the previous delivery.

4.5.2 Red Color and Particles in the Fuel

At the 23 July 2013 delivery, the Domestic delivery driver noticed a red tint to the fuel. Gevo determined that the red tint was coming from the truck's fuel hose. A red dye is used to tint off-road diesel fuels, such as marine diesel. Gevo explained that after years of use, the fuel tank hose had absorbed the dye, and subsequently the dye leached out to color the BU16 upon delivery. To avoid this practice in future deliveries, Domestic instituted a process to flush roughly 15 gallons of fuel (the estimated capacity of the fuel hose) through the hose before filling the trailerable tank at Yorktown.

On the same 23 July delivery, TRACEN Yorktown personnel reported particles in the fuel, and Gevo determined that the hose from the delivery truck caused this issue as well. The original hose (Goodyear Redwing Fuel Oil hose made of nitrile synthetic rubber) was replaced on 2 August 2013 with a Flexdraw hose (constructed of NBR- Nitrile Butadiene Rubber). The manufacturer of the Flexdraw hose states that it is compatible with BU16. No other issues with color or particles were reported throughout the yearlong operational test after installation of the new hose.

Although fuel delivery methods and logistics of fuel delivery were not part of the scope of this study, materials compatibility of existing fuel infrastructure needs confirmation in.

4.5.3 Washed/Unwashed Gum

After the delivery of fuel on 23 July 2013, sample test results for washed gum reported 6 mg/100mL, exceeding the ASTM D4814 limit of 5 mg/100mL. The unwashed gum content (48 mg/100mL) did not exceed the standard, but showed a marked increase from the sample taken from the first delivery on 19 June (9.0 mg/100mL). The RDC was concerned by the increase, since the two samples came from the same 10,000 gallon batch of fuel blended at the start of testing. Gevo responded to this concern indicating that given their current data, they did not believe that the unwashed gum content would change further, and that this anomalous test result was due to an initial residual of fuel in the truck.

After the fourth delivery of fuel on 18 October 2013, the levels of washed and unwashed gum were relatively high (no standard for unwashed gum). Upon investigation, Gevo determined that the fuel delivery truck and its piping were responsible for the contaminated fuel. The truck had been delivering diesel fuel for nearly twenty years, and Gevo indicated that despite a thorough cleaning, residue had contaminated the BU16 and caused the high readings. Gevo initially proposed to use tote tanks to deliver the fuel, taking the tank truck out of the loop, or to use a delivery truck that had only delivered gasoline. Due to state law restrictions on transporting fuel via tote tanks, Gevo decided to use a gasoline truck for future deliveries. As

further assurance, the truck was emptied, air dried and then flushed before any more deliveries were made. Problems with washed/unwashed gums did not reoccur on subsequent deliveries.

4.5.4 Crew Feedback

In addition to the quantitative data from the data collection system, the test team captured observations from the SPC-TB crew at TRACEN Yorktown during periodic visits. These visits also provided an opportunity to retrieve data, ensure the instrumentation was working properly and test protocols were being followed, and perform a visual inspection of the engines and exposed fuel systems. To assist in obtaining the most useful crew data, the test team provided training prior to the start of testing, including the following topics:

- Project background.
- Project goals; specifically for the biobutanol testing.
- Overview of biobutanol fuel; how it is made, advantages, disadvantages, and the Material Safety Data Sheet (MSDS).
- Differences between gasoline fuel and biobutanol fuel including the effects of temperature.
- Safety-related and health issues including safety regulations concerning exposure to biobutanol; i.e., skin contact, ingestion, etc.
- Observations of potential changes to maintenance requirements.
- Changes in Federal and State regulations concerning reporting of spills, etc.
- Changes in fuel logistics; i.e., biobutanol delivery/storage issues.
- Use/monitoring of data acquisition system.

During the visits, the test team asked the following questions:

1. <u>Have you noticed any difference in boat performance between E0 and BU16?</u> (The test team prompted the crew by asking about specifics such as differences in acceleration, throttle response etc.). Over a year of testing and more than a dozen different crewmembers, the consensus was that there was no difference.
2. <u>If you were not told what fuel you were using, would you be able to tell whether it was E0 or BU16?</u> This was asked in the context of a well-running engine and focused on performance. The test team was looking for small nuances of the impact of BU16, such as “the engines seemed sluggish” or “they don’t seem as fast” etc. All of the responses indicated there was no difference in performance detected.
3. <u>Have there been any maintenance events with the BU16 that are not encountered with standard E10 fuels?</u> There were no BU16-related maintenance issues.
4. <u>Do you see any reason why BU16 could not be used as an operational fuel (assuming the logistics of delivery and storage are solved)?</u> No concerns were voiced.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

5.1.1 Overall Result

Based on the testing in this study, BU16 appears to be an acceptable alternative fuel for E10 gasoline, for the engines tested and within the environmental conditions experienced. The impact of BU16 on boat performance and maintenance was no different than when using E10. One potentially desirable property of

isobutanol when compared to ethanol is that if the fuel is exposed to a sufficient amount of water to form a 2-phase mixture, ethanol primarily favors the aqueous phase whereas the isobutanol favors the non-aqueous phase. This could offer a significant benefit in the marine environment, where engines are constantly exposed to water. Issues that need further study include the rising levels of butanol noted during storage and material compatibility in the fuel distribution infrastructure.

5.1.2 Performance

Based on test data and crew observations, the test team and SPC-TB coxswains and crewmembers perceived no performance difference when operating on BU16 fuel, compared to E10. SPC-TB performance was no different whether the fuel was E10, BU16, or whether both fuels were mixed together.

5.1.3 Maintenance

SPC-TB crewmembers and maintenance personnel detected no effect on maintenance between operating on E10 or BU16. In addition, after testing for materials compatibility, and visually examining engine components following bench testing, Mercury detected no difference between the effects of E10 and BU16.

5.1.4 Fuel Quality and Logistics

Although the logistics of fuel distribution, storage and handling was not the focus of this study, a number of issues were noted. Because biobutanol is developmental, many aspects listed below that support a commercially available fuel supply do not currently exist for BU16. The test team assumes that normal market processes will resolve many of the issues, such as storage, price, distribution, and quality.

- Availability: extremely low quantities produced.
- Competition: one U.S. source at this time (Gevo) and one in development (Butamax Advanced Biofuels, LLC).
- Price: unknown, although assumed to be competitive with gasoline to be commercially viable.
- Distribution network: could use existing gasoline distribution network if materials compatibility is confirmed.

The logistics required for this operational test impacted the outcome. A large quantity single batch of blended BU16 fuel was required to be mixed for the testing due to economic considerations. The test fuel was blended using summer base gasoline with a low RVP. The test team believes that the high butanol/low RVP fuel was a result of using summer base gasoline and long storage times. If a robust, fresh supply of fuel is available, these issues could be avoided.

5.1.5 Emissions

Based on Mercury's testing, the test team considered the emissions using BU16 or E10 to be relatively similar. Mercury concluded that for the engines tested:

- Hydrocarbon (HC) and CO emissions are lower with oxygenated fuel. The open-loop Mercury engines run leaner with oxygenated fuel, therefore generating lower HC and CO emissions when compared to E0.

- Emissions of oxides of Nitrogen (NOx) are higher with oxygenated fuel than with E0. NOx generation is a function of the time spent at high temperature/pressure in the combustion chamber due to the leaner burning caused by the increased oxygenation. The engines run leaner with oxygenated fuel, which generates higher NOx emissions.

5.2 Recommendations

5.2.1 Cold Weather Testing

Ambient temperature ranged between 24and 99 degrees F during the test period. Cold weather testing should be conducted in a location where severe cold weather will commonly be experienced in the winter months, such as New England, Alaska, or in the Great Lakes prior to the onset of ice.

5.2.2 Butanol Storage

The high percentages of butanol that the test fuel experienced during the operational testing should be investigated further. The manufacturers, suppliers and users of biobutanol will need to verify that the increase in butanol percentage noted during this testing does not occur during storage conditions. The USCG should continue to monitor this issue to confirm that it does not reoccur.

5.2.3 Infrastructure Materials Compatibility

The materials compatibility for the test engines were verified by Mercury Marine during the operational test. Although not part of the scope of this test, existing distribution infrastructure materials compatibility with BU16 needs to be confirmed as well. The current producers of biobutanol (GEVO, Butamax) have done extensive materials testing through independent laboratories on existing gasoline distribution infrastructure components. The USCG should monitor these results to confirm that the existing USCG infrastructure is compatible with BU16.

5.2.4 Long Term Commercial Viability

This was a focused study that examined the performance of biobutanol as an engine fuel using E10 as the reference on the particular test engines. The test team found that BU16 is a suitable drop-in replacement for E10. Since biobutanol has not yet come to market, aspects of supplying BU16 for this test affected its outcome. Once the fuel is commercially available; its further evaluation and use are recommended.

We recommend that the Coast Guard undertake some simple measures to position itself for the future availability of this fuel.

- Continue to monitor the commercial production capability of biobutanol producers as they bring their product to market.
- Once commercial availability has been established, consider adding biobutanol fuel capability as an added requirement for future outboard engine procurements.
- Ensure issues noted in this report (butanol storage, infrastructure compatibility) are satisfactorily addressed.

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APPENDIX A. ALTERNATIVE FUEL EVALUATION MATRIX

Table A-1. Alternative fuel evaluation matrix.

								Candidate Gasoline Alternative Fuels											
								Gasoline (E10)		CNG (3)		LNG (3)		Biobutanol		Ethanol (E85)		Biomass-to-Liquids	
	Category	Attribute		Importance Weighting Factor (WF) (2)	Attribute Rankings (1)	High Score	Low Score	WF	WF*Imp Rating	WF	WF*Imp Rating	WF	WF*Imp Rating	WF	WF*Imp Rating	WF	WF*Imp Rating	WF	WF*Imp Rating
1	Economic Factors	Fuel Cost	Alt Fuel Cost on a per gallon or gallon equivalent basis.	3	1=Significant Increase over baseline	9	3											1	3
					2=Moderate increase over baseline									2	6	2	6		
					3=Same cost or less than baseline			3	9	3	9	3	9						
2	Economic Factors	Modification Cost	Cost associated with modifying the ACTD for use of the proposed Alternative fuel.	2	1=Significant, > $500K	6	2												
					2=Mid Range, $100K - $500K					2	4	2	4			2	4		
					3= Moderate, <$100K			3	6					3	6			3	6
3	Maturity	Availability	Alternative Fuel available with distribution support for 2011-2012 ACTD	3	1= Experimental (Laboratory) with little or no support.	9	3												
					2= Prototype Development with some support.									2	6			2	6
					3= Mature (Commercially Available) and well supported.			3	9	3	9	3	9			3	9		
4	Maturity	OEM Approval	Engine OEM Approval for fuel	2	1=No	4	2			1	2	1	2	1	2			1	2
					2=Yes			2	4							2	4		
5	Maturity	Marine Applications	Marine Applications	2	1= No Known Applications	6	2							1	2	1	2	1	2
					2= Experimental Applications Only														
					3= In use by Marine Industry			2	6	3	6	3	6						
6	Maturity	Transit Applications	Transit Applications	2	1= No Known Applications	6	2											1	2
					2= Experimental Applications Only									2	4				
					3= In use by Transit Industry			2	4	3	6	3	6			3	6		
7	Maturity	Vendors	Vendors:	3	1=No vendors (Laboratory Only)	9	3												
					2=Few vendors							2	6	2	6			2	6
					3=Ample vendors			3	9	3	9					3	9		
8	Performance	Carbon Footprint	Reduction in Carbon Footprint (GHG) from Baseline Fuel (Regular Gasoline)	3	1=No reduction in Carbon Footprint	9	3												
					2= moderate reduction in Carbon Footprint (≤ 50%)			2	6	2	6	2	6	2	6	2	6		
					3 =Substantial reduction in Carbon Footprint (≥ 50%)													3	9
9	Performance	Engine Performance	Effect on ACTD Engine HP	3	1=Degraded	9	3			1	3								
					2=No effect			2	6			2	6	2	6	2	6	2	6
					3=Improved														
10	Performance	Fuel Consumption	Specific Fuel Consumption: (SFC)	3	1=Increase	9	3	1	3	1	3	1	3	1	3	1	3		
					2=No effect													2	6
					3=Decrease														
11	Performance	Engine Exhaust Emissions	Impact on Engine Exhaust Emissions (CACs- NOx, SOx, HC, CO, and PM)	2	1=Little to no Reduction	6	2												
					2=Some Reduction			2	4					2	4	2	4		
					3=Significant Reduction					3	6	3	6					3	6
12	Performance	Endurance	Endurance (Range)	2	1= Use of Fuel will result in significant reduction of ACTD endurance	6	1			1	2	1	2			1	2		
					2= Use of Fuel will result in moderate reduction of ACTD endurance														
					3= Use of Fuel will result in little or no reduction of ACTD endurance			3	6					3	6			3	6
13	Physical	Engine Modifications	Engine Modifications Required	2	1=Major modifications required to engine.	6	2			1	2	1	2			1	2		
					2=Minor modifications required													2	4
					3=No modifications required			3	6					3	6				
14	Physical	Boat Modifications	Boat Modifications Required	2	1=Major modifications required.	6	2			1	2	1	2						
					2=Minor modifications required											2	4	2	4
					3=No modifications required			3	6					3	6				
15	Physical	Boat Weight	Weight effect on ACTD Boat	3	1= Significant Increase	9	3			1	3	1	3						
					2=Some Increase									2	6				
					3= Decrease or no Increase			3	9							3	9	3	9
16	Physical	Fuel Volume (capacity)	Volume Effect on ACTD	3	1= Significant Increase	9	3			1	3	1	3						
					2=Some Increase														
					3= Decrease or no Increase			3	9					3	9	3	9	3	9
17	Physical	Fuel Storage	Special Fuel Storage	3	1= Extensive requirements	9	2			1	3	1	3						
					2= Some requirements											2	6		
					3= No special requirements			3	9					3	9			3	6
18	Reliability	Reliability	Reliability/Durability	2	1= Degraded	6	2									1	2		
					2= Little or no effect			2	4	2	4	2	4	2	4			2	4
					3=Improved														

Table A-1. Alternative fuel evaluation matrix (cont.).

								Candidate Gasoline Alternative Fuels											
								Gasoline (E10)		CNG (3)		LNG (3)		Biobutanol		Ethanol (E85)		Biomass-to-Liquids	
	Category	Attribute		Importance Weighting Factor (WF) (2)	Attribute Rankings (1)	High Score	Low Score	WF	WF*Imp Rating	WF	WF*Imp Rating	WF	WF*Imp Rating	WF	WF*Imp Rating	WF	WF*Imp Rating	WF	WF*Imp Rating
19	Safety	Toxicity	Toxic Properties: Causes injury or death if inhaled, ingested, or contacted.	3	1=Highly Toxic 2=Somewhat Toxic 3=Non-Toxic	9	3	2	6	3	9	3	9	3	9	3	9	3	9
20	Safety	Explosive	Explosive Properties	3	1=Highly Explosive 2=Somewhat explosive 3=Non-explosive	9	3	1	3	1	3	2	6	2	6	2	6	2	6
21	Safety	Flash Point	Flash point as compared to the flash point of the baseline fuel (Regular Gasoline).	3	1= Less then the baseline fuel 2= The same as the baseline fuel. 3= Greater then the baseline fuel.	9	3	2	6	1	3	1	3	3	9	3	9	3	9
22	Logistics	Regulations	Governing Regulations	2	1=Extensive Regulations 2=Few Regulations 3=No regulations	6	2	1	2	1	2	1	2	2	4	1	2	3	6
23	Logistics	Specifications	Fuel Specification	3	1=Fuel not produced to ASTM or equivalent Fuel Std. 2=Fuel not produced to ASTM or equivalent Fuel Std but certified. 3=Fuel is produced to ASTM or Equivalent Gasoline Fuel Std	9	3	3	9	3	9	3	9	2	6	3	9	1	3
24	Lessons Learned	Benefits	Benefits	2	1= Few to No Benefits 2= Some Benefits 3= Major Benefits	6	2	2	4	3	6	3	6	3	6	2	4	3	6
25	Lessons Learned	Drawbacks	Drawbacks	2	1= Major Drawbacks 2= Some Drawbacks but not of major consequence. 3= No drawbacks	6	2	2	4	2	4	1	2	2	4	1	2	2	4
					Totals	187	61	58	149	47	118	47	119	56	141	51	134	56	139
					Scale of 1-10	10	1	NA	8.0	NA	6.3	NA	6.4	NA	7.5	NA	7.2	NA	7.4

Notes:
(1) If information is not available for an attribute for whatever reason (For example The technology is in the developmental state and certain parameters have not been established) then a zero is assigned in the Matrix.
(2) Attributes Importance Weighting Factors: 1= Important, 2 = Moderately Important, 3 = Very Important
(3) Includes bi-fuel systems where gasoline and natural gas are used in combination to exploit the advantages of both fuels.

APPENDIX B. BUTANOL/GASOLINE TEST PLAN

The Butanol/Gasoline Test Plan is provided as a separate electronic document to comply with file size limitation requirements.

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APPENDIX C. DRAFT SPC-TB TIME COMPLIANCE TECHNICAL ORDER (TCTO)

Draft Gasoline Time Compliance Technical Order (TCTO):
Data for Input to TCTO Phase 1 Form (Section 1)

Contract No. HSCG32-10-D-R00021
Task Order HSCG32-11-J-300018, Deliverable 4
Project 4103 – Operational Testing of Alternative Fuels

31 January 2012

1. Case File #: [leave blank]
2. TCTO #: [leave blank]
3. Type: SPC-TB
4. Title: Modification for Alternative Fuel Testing (Biobutanol) on CG-38011 (Yorktown, VA)
5. Submitted by: Coast Guard Research & Development Center
6. Submission Date: [leave blank]
7. Desired Installation Date: 17 September 2012
8. Requirement/Description: See Table 1, which lists changes recommended to CG-38011 prior to commencement of biobutanol (BU16) testing. Table 2 contains cost details for all recommended items.

Distribution Statement A: Approved for public release; distribution is unlimited.
1 of 4

Table 1. Recommended Changes to SPC-TB CG-38011 to Support BU16 testing.

Task	Description	Rec.	May Need to be Done	Comments
1	**Fuel Tanks**			
a	Compatibility		X	In general, butanol has not been found to have adverse effects on any materials typically found in gasoline fuel systems. Aluminum, such as the fuel tank on the SPC-TB, has not been tested yet; however, Butamax is in the process of doing materials testing on samples provided by the manufacturer with results expected summer 2012.
2	**Fuel System Modifications**			
a	Gasket on fuel tank sending unit		X	Gasket provided by WEMA USA; they can provide nitrile, cork/nitrile, or Viton gasket. Need to check with tank manufacturer or unit to determine what was used on CG-38011.
b	Replace metallic fuel line fittings and components that are not compatible with the BU16 fuel.		X	Brass, bronze, copper, lead, tin, and zinc may accelerate the oxidation process creating fuel insoluables or gels and salts. Lead solders and zinc fittings should also be avoided. These are found in fuel tank shut off valves, fuel tank connection fittings, and fuel filter manifold connection. Waiting for feedback from Butamax and Gevo on metallic material compatibility issues.
c	Modify or change out fuel filters/water separators.		X	Both the fuel filter manifold and fuel filter/water separator are aluminum; if aluminum is determined to be incompatible with butanol (unlikely), then these will need to be changed out.
3	**Instrumentation**			
a	FloScan fuel flow meter	X		The FloScan meters need to be confirmed to be compatible with the Mercury Verado engines, and BU16. The body of the FloScan transducer is either zinc or aluminum; this needs to be determined. Zinc should be replaced; aluminum may be OK (see comment 1a above).
b	Nav box	X		A data collection (nav) box will be installed in a location that is determined to not interfere with operational requirements. This nav box will have a GPS receiver (L1 DGPS or WAAS), heading/pitch/roll sensors, a data collection computer (such as the Moxa UC-8418 embedded computer) for long-term data collection and a weather station (such as Maretron WSO100) installed in it. The nav box will require 24 VDC and the mounting of the GPS and weather station antennas.

2 of 4

Table 1. Recommended Changes to SPC-TB CG-38011 to Support BU16 testing.

Task	Description	Rec.	May Need to be Done	Comments
4	**Engine Modifications**			
a	Change out metallic and non-metallic parts that are not BU16-compatible based on results of Honda and Mercury material testing.		**X**	Modify engines as recommended by Mercury. Waiting for results of their testing, which will be available OOA 16 July 2012.
5	**Miscellaneous**			
a	Provide extra fuel filter elements.		**X**	If the existing fuel filters are NOT compatible with BU16 and specialized fuel filters are needed, then extras need to be provided to the unit. Waiting for feedback from Butamax and Gevo on fuel filter issues.
b	Restore SPC-TB to pre demonstration configuration.		**X**	Return test boat to the standard configuration.

Table 2. Cost Details for each TCTO Item.

TCTO Line #	Item/Service	Suggested Manufacturer	Suggested Part Number	Qty	Cost Each	Sub-Total	Install Cost	Total Cost	Notes
1a	Fuel tank			1					**Note 1:** A requirement for these potential items will be determined upon receipt of results of material testing and costs estimated at that time.
2a	Gasket			1					
2b	Fuel fittings			1					
2c	Fuel filters			1					
3a	Fuel flow meter	FloScan	20B Series	1	$3,295	$3,295	$1,000	**$4,295**	**Fuel monitoring system subtotal estimate** (compatibility to be determined)
3b	Nav box: Weather station/GPS	New Mountain	NM100 Weather Station	1	$1,400	$1,400	$0	$1,400	
	Nav box: Data collection computer	Moxa	IA261-I/262-I Series	1	$1,250	$1,250	$0	$1,250	
	Nav box: Inertia Measurement Unit (IMU)	Honeywell	HMR2300	1	$850	$850	$0	$850	
	Nav box: Enclosure, power supply, misc cables	SKB, miscellaneous	Miscellaneous	1	$800	$800	$0	$800	
			Subtotal	**1**	**$4,300**	**$4,300**	**$0**	**$4,300**	**Nav box subtotal estimate** (install to be done by test team; estimated 4 hrs)
4a	Incompatible engine parts								See Note 1 above.
5a	Extra fuel filters			30					See Note 1 above.
								$8,595	**Total estimate for SPC-TB**

4 of 4

APPENDIX D. MERCURY MARINE TEST REPORT

Acquisition Directorate
Research & Development Center

United States Coast Guard Isobutanol Study – Mercury Marine

A Study of Using Gasoline with 16% Isobutanol

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December 2012

Homeland Security

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United States Coast Guard
Research & Development Center
1 Chelsea Street
New London, CT 06320

United States Coast Guard Isobutanol Study – Mercury Marine

Technical Report Documentation Page

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United States Coast Guard Isobutanol Study – Mercury Marine

EXECUTIVE SUMMARY

1.1 Objective:

The objective of this work was to understand the effects of using a 16% isobutanol blend on a 300HP supercharged outboard marine engine. The testing and evaluation was divided into 3 parts: 1. fuel system fuel compatibility bench testing, 2. dynamometer running engine evaluation, and 3. boat driveability evaluation.

1.2 Summary of Results:

Fuel System Bench Test:

- All fuel system components performed within specification after exposure to butanol test fuels as defined by test procedure and engine requirements.
- Changes in elastomer material properties were observed equally in baseline and butanol fuels. All components maintained system and component function regardless of changes to material properties.
- One of two fuel filters exposed to 16% butanol exhibited increased flow restriction that was not attributed to material degradation of tested components. The cause of restriction suspected to have resulted from unintended contaminate within fuel reservoir at test facility or during post flow test evaluation. The measured increase in differential pressure would not have impeded normal engine performance.

Dynamometer Evaluation:

- The power output was slightly higher when using butanol fuel.
    - Most of the difference in power can be attributed to higher airflow due to better intake air cooling (thus higher density) from the alcohol fuel.
- The hydrocarbon (HC) and carbon monoxide (CO) emissions are lower with butanol fuel.
    - This open-loop fuel controlled engine runs leaner with oxygenated fuel, therefore generating lower HC and CO emissions.
- The emissions of oxides of nitrogen (NOx) are higher with butanol fuel.
    - NOx generation is a function of the time spent at high temperature/pressure in the combustion chamber. The engine runs leaner with oxygenated fuel, which generates higher NOx emissions.
- There was very little fuel dilution of the engine lubricating oil with all 3 fuels.

- The butanol fuel was blended at 90 octane [R+M]/2, which was 2-4 octane numbers below the other fuels in the test.
    - As such, the other fuels had higher margin to spark knock than the butanol fuel, but there is still sufficient margin at the baseline spark timing using the butanol fuel.

Boat Driveability Evaluation:

- There were no notable differences in run quality between the various fuels when operated on a boat during a variety of steady-state and transient maneuvers.

1.3 Conclusions and Recommendations:

No issues were uncovered in this evaluation that would deter the USCG from continuing on with the operational testing of the 16% isobutanol blend fuel. The performance of the Verado engine while using 16% isobutanol blended fuel should be equivalent to performance when using E0-E10 gasoline.

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United States Coast Guard Isobutanol Study – Mercury Marine

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS

Bu16	16% isobutanol/84% gasoline blend fuel
HP	Horsepower
EPA	Environmental Protection Agency
EEE	Emissions reference test fuel – no ethanol
E10	10% Ethanol/90% gasoline blend fuel
E0	Gasoline with no ethanol blending
HC	Hydrocarbons
CO	Carbon Monoxide
NOx	Oxides of Nitrogen
COV of IMEP	Coefficient of Variation of Indicated Mean Effective Pressure
COV of RPM	Coefficient of Variation of Revolutions per Minute
RVP	Reid Vapor Pressure

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2 INVESTIGATION DETAILS

2.1 Statement of Problem

This project supported initiatives to assist the USCG to develop strategies to monitor and reduce the amount of greenhouse gas emissions. The work was a cooperative effort between the USCG and Mercury Marine (a division of Brunswick Corporation) to assess the feasibility for marine engines of using a butanol blend fuel. Specifically, a 16% isobutanol / 84% gasoline fuel blend (Bu16) was tested on a current production 300HP supercharged EFI four-stroke outboard engine. The testing was performed to determine if the butanol fuel blend would be acceptable to perform operational testing for a 12 month period at the USCG Research and Development Center.

2.2 Test Engine Description

The engine used for this testing was the supercharged 300HP Verado four-stroke outboard engine. The Verado engine is considered the "flagship" outboard product at Mercury Marine. The non-Racing version used in this study is available in power outputs ranging from 225-300HP. These engines are used on boats with single, dual, triple, and even quad engine installations ranging from multi-engine offshore fishing boats & US Coast Guard patrol boats, high speed inshore fishing boats, all the way to commercial fishing vessels and ferry boats. The 300HP Verado is the engine type that will be used by the US Coast Guard in their portion of this study, which is why this engine was chosen. The Verado engine has an open loop electronic fuel injection system with no user adjustment possible.

Table 1: Test Engine Specifications

Engine Family	Verado
Gas Exchange Process	Four-Stroke
Power Rating at Prop	300HP
Cylinder Configuration	Inline 6 Cylinder
Displacement	2.59 Liter
Fuel Induction System	Supercharged Electronic Fuel Injected 4 Valve per Cylinder, Dual Overhead Cam, Electronic Boost Control, Electronic Knock Abatement Strategy
Dry Weight	635 lbs / 288 kg
Fuel Octane Requirement	92 Octane R+M/2 Recommended, 87 Octane R+M/2 Minimum Required

2.3 Test Fuel Evaluation

2.3.1 Fuel System Bench Test:

Four blends of fuel were used to investigate materials compatibility of the fuel system: 1. 87 octane unleaded E0, 2. 84% 87 octane unleaded + 16% Butanol, 3. 84% ASTM D-471-79 Ref C+ 16% Aggressive Butanol, and 4. 83.7% ASTM D-471-79 Ref C fuel+ 16% Butanol+ >0.3% Tertiary Butyl Hydro-Peroxide.

Fuel blend 3 was defined per Oak Ridge National Laboratory recommendation, a special blend of aggressive Butanol in the formulation of: 1. 0.099% deionized water, 2. 5 ppm sodium, 3. 25 ppm sulfuric acid, and 4. 75 ppm isobutyric acid, was used as an aggressive test fluid for materials compatibility. The aggressive isobutanol formulation is blended with reference fuel C at the isobutanol concentration of interest. For example, at 16% (by volume) isobutanol, the aggressive fluid formulation would be comprised of 84% (by volume) reference fuel C and 16% (by volume) aggressive isobutanol.

2.3.2 Dynamometer Evaluation:

The fuels used in the running engine testing were intended to be representative of typical pump-grade fuels that could be commonly available to the general consumer or commonly used reference-grade fuel to establish the baseline. Three fuels were evaluated in the dynamometer testing: 1. 16% isobutanol blend, 2. emissions reference fuel (EPA Tier II EEE fuel), and 3. pump-grade premium octane 10% ethanol blend. The primary factors in sourcing the Bu16 test fuel were consistency of fuel properties for the duration of testing, accuracy of butanol content at 16%, octane performance that met the requirements of the test engine, and a representative distillation curve to match charge preparation characteristics. The Bu16 test fuel was blended by a fuel supplier in one batch to ensure consistency throughout testing. Since the Verado engine had a premium fuel recommendation, the butanol fuel was blended at a target of 90 octane [R+M]/2. The blend stock used was a reference-grade fuel that the fuel blender had on-hand. The emissions reference EEE fuel and the 16% isobutanol fuel were sourced from specialty fuel manufacturer Johann Haltermann Ltd. The E10 fuel used for testing was typical pump-grade fuel that the fuel distributor had available for distribution locally and was not from the same supplier as the other fuels.

Samples of the fuels were analyzed to characterize them and the results can be seen in Table 2 below. Two of the most important aspects to consider about the fuels that had a large influence on the testing performed on the dynamometers were the distillation curves and the octane values of the fuels. The distillation curve results are shown in Figure 1 below. The shape of the distillation curve can affect several of the tests conducted including the oil dilution test, emissions, driveability, etc. Table 3 below summarizes the difference in octane values of the fuel. The pump-grade E10 fuel was analyzed by a different method than the Bu16 and emissions reference fuel, so the results may not be directly comparable. The Bu16 and emissions reference fuel were analyzed with ASTM D2699 and D2700, which are the actual running engine knock tests. The pump-grade E10 was analyzed with a chemical analyzer utilizing the infrared spectroscopy concept (ASTM D5845) and the results are shown as a reference only. The octane results indicate that the pump-grade E10 fuel should tolerate more spark advance during the knock tolerance test, followed by the emissions reference fuel and then the Bu16 fuel.

United States Coast Guard Isobutanol Study – Mercury Marine

Table 2: Fuel Analysis Results

	16% Butanol	EEE E0 Emiss. Ref.	Test Standard
Density	0.7464	0.743	ASTM D1475
Heat of Combustion			ASTM D240
Gross	18784 BTU/lb		
Net	17566 BTU/lb	18490 BTU/lb	
Carbon	82.23%	86.31%	ASTM E191
Hydrogen	13.35%	13.34%	ASTM E191
Copper Corrosion	Slight Tarnish, 1A	1A	ASTM D130
Water Tolerance	-42°C		ASTM D6422
Doctor Test	negative		ASTM D4952
Existent Gum	<0.2 mg/100mL		ASTM D381
	<0.2 mg/100mL	<0.5 mg/100mL	ASTM D381
Potential Gum			ASTM D873
Unwashed gum	<0.2 mg/100mL		
precipitate	0 mg/100mL		
insoluble gum	0 mg/100mL		
Oxygen	4.42%	0%	
Karl Fischer Water	200 ppm		ASTM E203
Sulfur	4.1 ppm	29 ppm	ASTM D5453
Oxygen Stability	1000+ minutes	1000+ minutes	ASTM D525

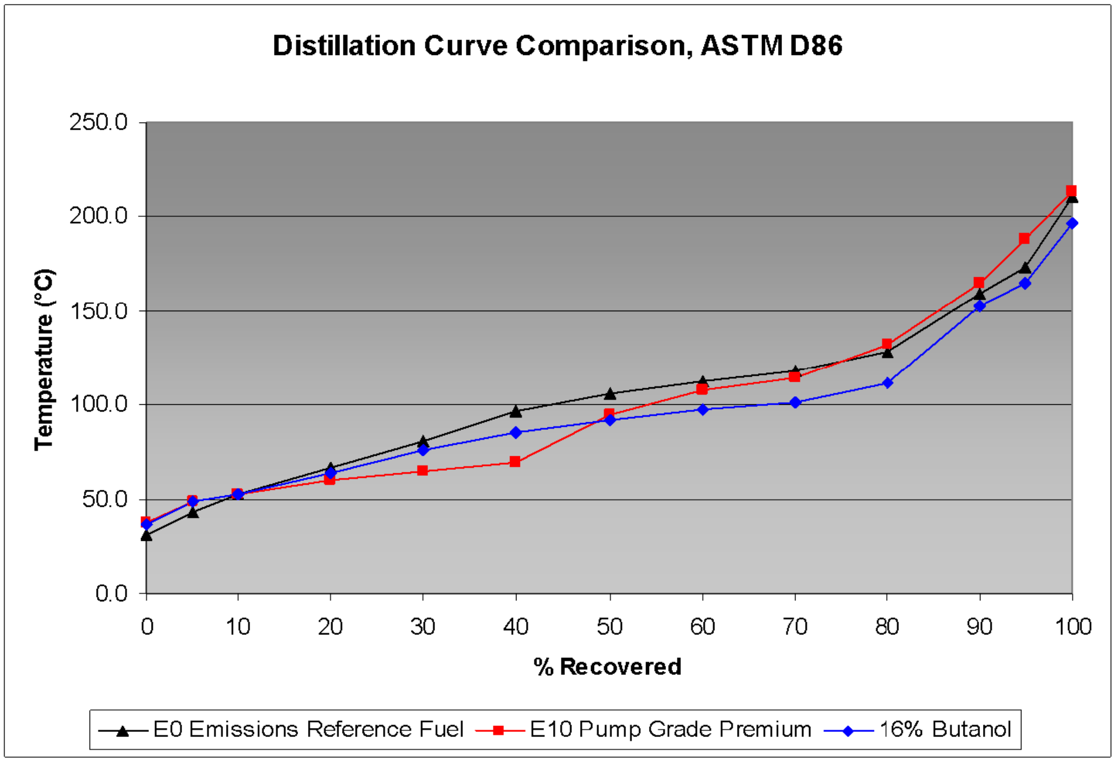

Figure 1: Distillation Curves of Test Fuels

Table 3: Octane Measurement Summary

	16% Butanol	EEE E0 Emiss. Ref.	Test Standard	Pump-Grade E10	Test Standard
RON	95	96.6	ASTM D2699	99.8	ASTM D5845
MON	85.4	88.6	ASTM D2700	89.3	ASTM D5845
[R+M]/2	90.2	92.6		94.6	

2.3.3 Calibration Driveability Evaluation:

The Bu16 fuel used for the driveability testing was from the same batch that was used for the dynamometer testing so the results are shown in the section above. The E0 pump-grade baseline fuel used for the driveability testing was not analyzed so no results are given here.

2.4 Procedure

2.4.1 Fuel System Bench Test:

The first step of the study was to evaluate the materials compatibility of the fuel system when exposed to an aggressive blend of isobutanol fuel. Eight 2011 L6 Verado fuel systems were sourced to Testing Services

Group, LLC for testing. A sample size of two fuel systems were tested in each test fuel, E0 gasoline, Bu16, Reference C fuel with aggressive Bu16, and a blend of Reference C with Bu16 containing >0.3% Tertiary Butyl Hydro-Peroxide.

The testing process began by properly filling each fuel system with the intended test fluid per Mercury specification defined within the test procedure. Once all units were filled, the fuel systems remained in a controlled environment maintained at 60° C throughout the test duration of 30 days. Fuel changes were performed at weekly intervals (7.25 +/- 0.25 days), with the exception of test fluid: Reference C with aggressive Bu16, which remained in system for the duration of the test.

Upon completion of test duration, the fuel systems were purged of remaining fluid and closed. The parts were sent to Mercury for post-test evaluations of components at Mercury or respective component manufacturer.

2.4.2 Dynamometer Evaluation:

The engine testing process began by preparing each engine. This included instrumentation of the test engines as well as performing standard checks. The instrumentation process included installation of an exhaust emissions probe that met the requirements of the EPA 40 CFR Part 91 regulations.

The engine was rigged onto an appropriate dynamometer and testing was performed. The power was measured to determine the wide open throttle (WOT) performance of each fuel. The power run was performed on E0 gasoline, Bu16 fuel, and also on pump-grade premium (high octane) 10% ethanol fuel (E10). The power run included speed points from 2000RPM up to the maximum rated speed of the engine.

Once the WOT performance was measured, emissions testing was performed using reference-grade E0 gasoline (EEE fuel: EPA Tier II emissions reference grade fuel). Emissions tests were also performed using the Bu16 test fuel and the pump-grade E10 fuel. Although the Bu16 test fuel and the pump-grade E10 fuel were not blended from the emissions reference E0 gasoline, these tests provide some comparison of exhaust emissions between E0, E10 and Bu16 while minimizing engine-to-engine variability.

After the emissions test, the 3 fuels were tested to ascertain the propensity for the fuel to collect in the oil sump. The engine was operated at a steady-state speed and load to deliver high fueling rates. Oil samples were collected periodically through the duration of the test. After testing was complete, the oil samples were analyzed via a distillation method to determine the percentage (by volume) of fuel collected in the oil.

The knocking tendencies of the 3 fuels were also evaluated on the dynamometer. The engine was operated at several steady state full load points and a part load point while being supplied temperature and humidity controlled air. The spark advance was varied at these operating conditions until the measured amount of knock reached the predetermined threshold. The knock control system built into the engine controller was disabled during this test so the knocking tendencies of the fuels could be evaluated without interference. The knock was measured via in cylinder pressure transducers.

The final test performed on the dynamometer was to check the run quality characteristics of the engine when operated with the 3 test fuels. The engine was operated at steady state at a variety of speed/load settings intended to capture the typical operating range that could occur during normal use. The in cylinder

pressure transducers were used to measure combustion characteristics. A statistical analysis of the cycle-to-cycle variability was calculated.

2.4.3 Calibration Driveability Evaluation:

After all of the dynamometer testing, a test engine was rigged on a test boat to perform on-water driveability testing. The test engine was a 300HP Verado, but it was not the same engine that was used for the dynamometer testing. The engine was rigged on a boat as a single engine, which differs from the dual engine installation used by the USCG. The boat used was a 21 foot Boston Whaler Justice model.

Lean operation from the difference in stoichiometric air/fuel ratio because of the butanol was the main factor considered for driveability. Maneuvers were performed that would exacerbate the lean operation from the butanol blends, such as rapid accelerations/decelerations, starting, and stability during shifting maneuvers. The maneuvers tested included starting (cold and warm), transient performance (hard acceleration, rapid deceleration, etc.), shifting performance/stability, and extended idle with drive-away.

All of the maneuvers were performed on the test engine on pump grade E0 and Bu16 fuels. The butanol fuel blend used on the boat testing was from the same batch of fuel as was used for the dynamometer testing, however the E0 fuel used on the boat was not the same fuel as the dynamometer testing.

2.5 Testing Results

2.5.1 Fuel System Bench Test:

Post testing results of bench tested components included manufacturer evaluation per each respective component performance specification. The vent canister performance evaluation was conducted at Mercury. The components evaluated consisted of: 1. fuel water separator filter, 2. all fuel hoses, 3. fuel injectors, 4. vent canister, and 5. fuel supply module (FSM).

The filters were analyzed by the production supplier, for flow restriction and leakage. Figure 2 below illustrates flow restriction to be equivalent within all fluids tested with exception of sample fuel 4b. Sample 4a and 4b components both were exposed to Ref C with Bu16. Sample 4b exhibited a flow restriction increase and was cause for further evaluation. Further evaluation of the filter revealed no visual signs of deterioration of material properties within the filter itself. It is also noted that components upstream of the filter may have caused contaminate to inhibit flow through filter. A hypothesis for the increased pressure drop is contaminant from the fuel tank or inlet supply fuel hose during butanol testing or during post-test evaluation caused restriction of sample 4b. It is not possible to evaluate these components to confirm the hypothesis as tank and inlet hoses (boat mounted hardware) were not included in scope of this study and were not retained. Regardless of root cause of increased pressure, normal engine performance would not be degraded by the increased restriction of filter sample 4b.

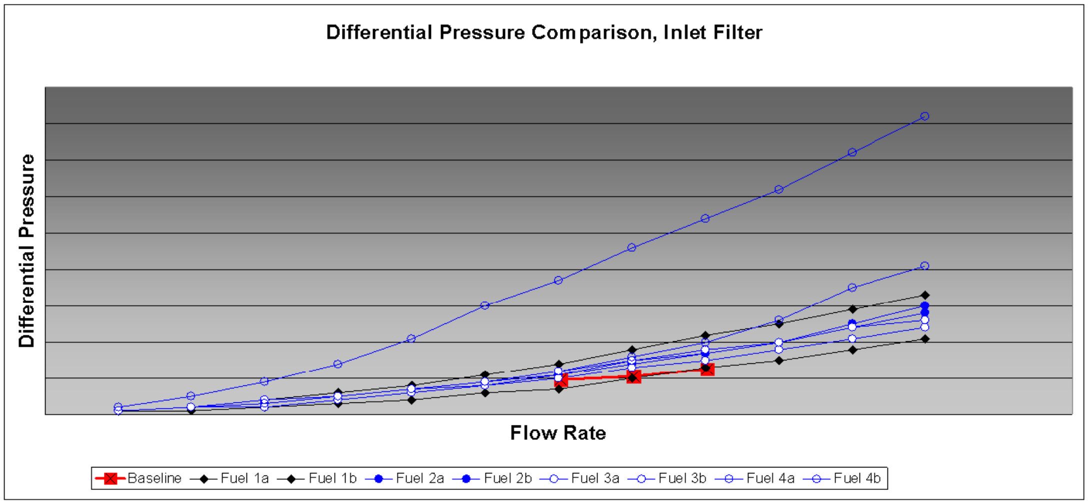

Figure 2: Flow Restriction Comparison

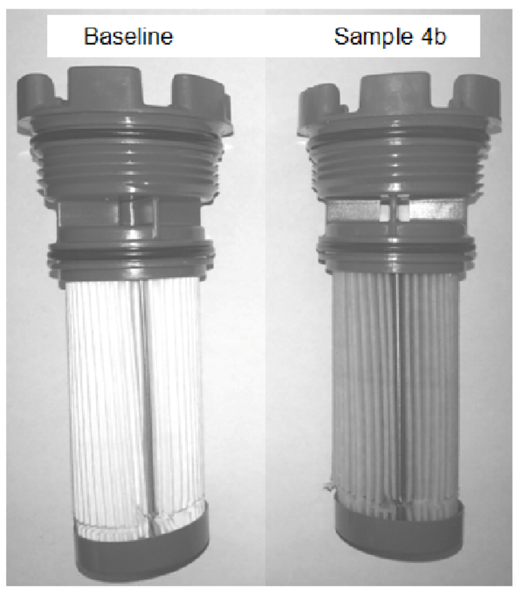

Figure 3: Inlet Filter Comparison

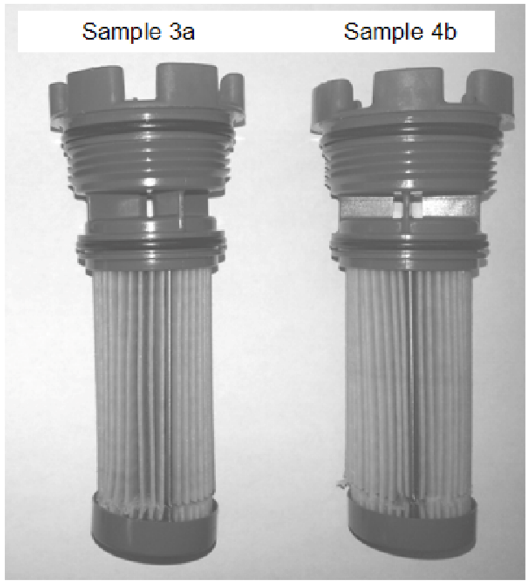

Figure 4: Inlet Filter Comparison

Figure 4 illustrates sample 4b contains no more contaminate than any other inlet filter media tested. All other filters appear to contain similar amounts of discoloration.

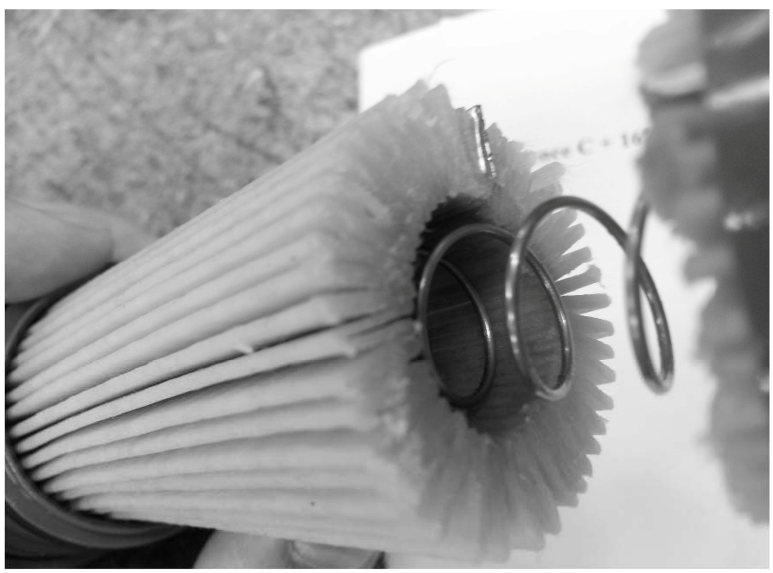

Figure 5: Inlet Filter Sample 4b

United States Coast Guard Isobutanol Study – Mercury Marine

The inspections of the inner and outer walls (Figure 5) in the filter sample 4b reveal no significant visual debris as a cause of increased restriction.

Fuel Hoses-

All fuel hoses were sent back to the production supplier for post-test inspection of leakage per component specifications. The hoses were tested at production supplier and results were within specifications of production tolerance.

Fuel Injectors-

All post tested fuel injectors for all fuels were within production tolerances as defined by flow and leakage rate.

Vent Canisters-

Vent canister post-test evaluations were done at Mercury. The vent canisters were evaluated for switch point location, leak test and air flow test as defined by component specification. All samples passed all performance requirements defined by component specification.

Fuel Supply Module-

All fuel modules passed post test evaluation for performance as defined by component specifications. Modules were tested for outlet pressure, current draw, wet flow, inlet suction and leak. All attributes performed at levels equivalent or greater than component specification. A further evaluation of the internal materials was conducted for reference to changes in material properties. The evaluation revealed all seals to be functional. However, one seal exhibited degradation of properties in all fuels and is cause for further investigation at Mercury Marine.

The high pressure pump outlet seal tested in butanol and non-butanol fuels appear to have swollen after exposure at 60°C for 30 days. Volume swell is the most likely contributor to the degradation of the cracked seals. Seals appear to have slid down over the radii of the fitting causing localized stretching. In this same location there is a ring of flash from the molding of the part that creates a disturbance in the surface. Near this location the component geometry contains sharp corners which contribute to stress concentration. The stressed conditions likely contributed to the failure in combination with the swelling of the rubber. It is also noted that the parts are about 20 durometer points softer post fuel exposure. This would most likely be due to the absorption of fuel or degradation of the material.

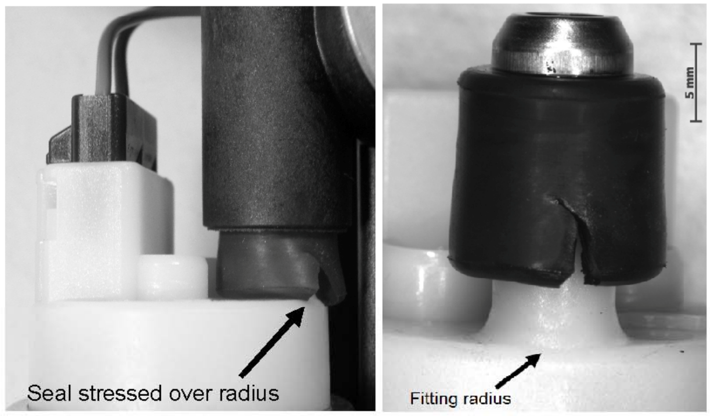

Figure 6: High Pressure Pump Outlet Seal

Figure 6 is taken from sample 1a, however, it is typical of all high pressure outlet seals.

The elevated temperature of 60°C during these accelerated tests is believed to be the major contributor to degradation of pump outlet seal. Historical data from bench and engine level testing do not indicate that this failure mode occurs in field operation. In field operation, temperatures typically do not reach 60°C.

2.5.2 Dynamometer Evaluation:

The power output was the first parameter investigated for this testing. Figure 7 below shows the results of the power testing. In general, the alcohol blend fuels generated slightly more torque than the E0 emissions reference fuel. The relatively small change in torque can be considered as essentially the same result. When operated with butanol fuel the engine produced the greatest amount of torque. Most of the difference can be attributed to higher airflow due to better intake air cooling (thus higher density) from the alcohol fuels.

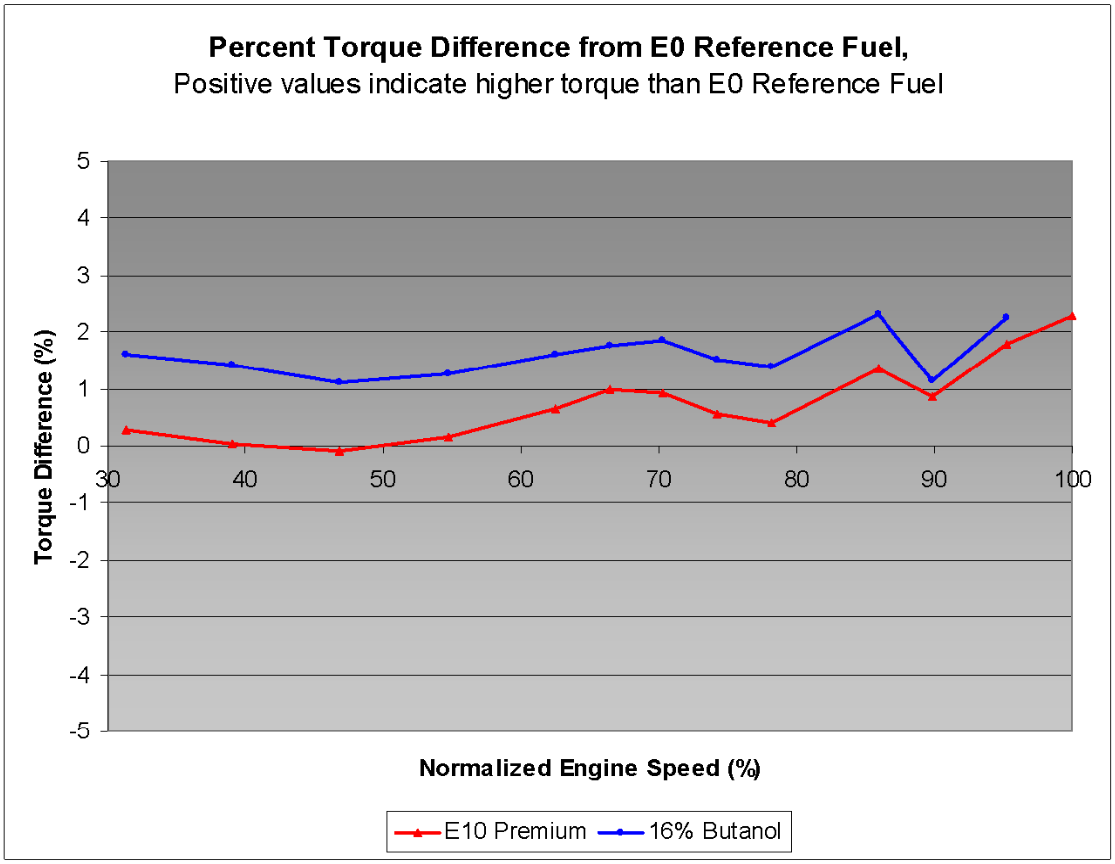

Figure 7: Torque Comparison

Since the butanol fuel has a lower stoichiometric air/fuel ratio compared with a typical non-oxygenated gasoline, it was expected that the open-loop fuel controlled engine in this test would run leaner. Figure 8 below supports this assumption. The equivalence ratio is defined as [stoichiometric air/fuel ratio] / [measured air/fuel ratio] so values greater than 1 are rich, and values less than 1 are lean. Figure 3 shows that both alcohol blend fuels run leaner than the E0 fuel as expected. The reason for targeting a 16% butanol mixture was to get the same oxygenate quantity as an E10 fuel, but Figure 8 shows that the Bu16 fuel runs slightly richer than the E10 fuel. Though the difference is slight (and could be from run-to-run measurement error), it could be caused by the slightly higher density of the butanol as compared with ethanol leading to a more-dense fuel blend.

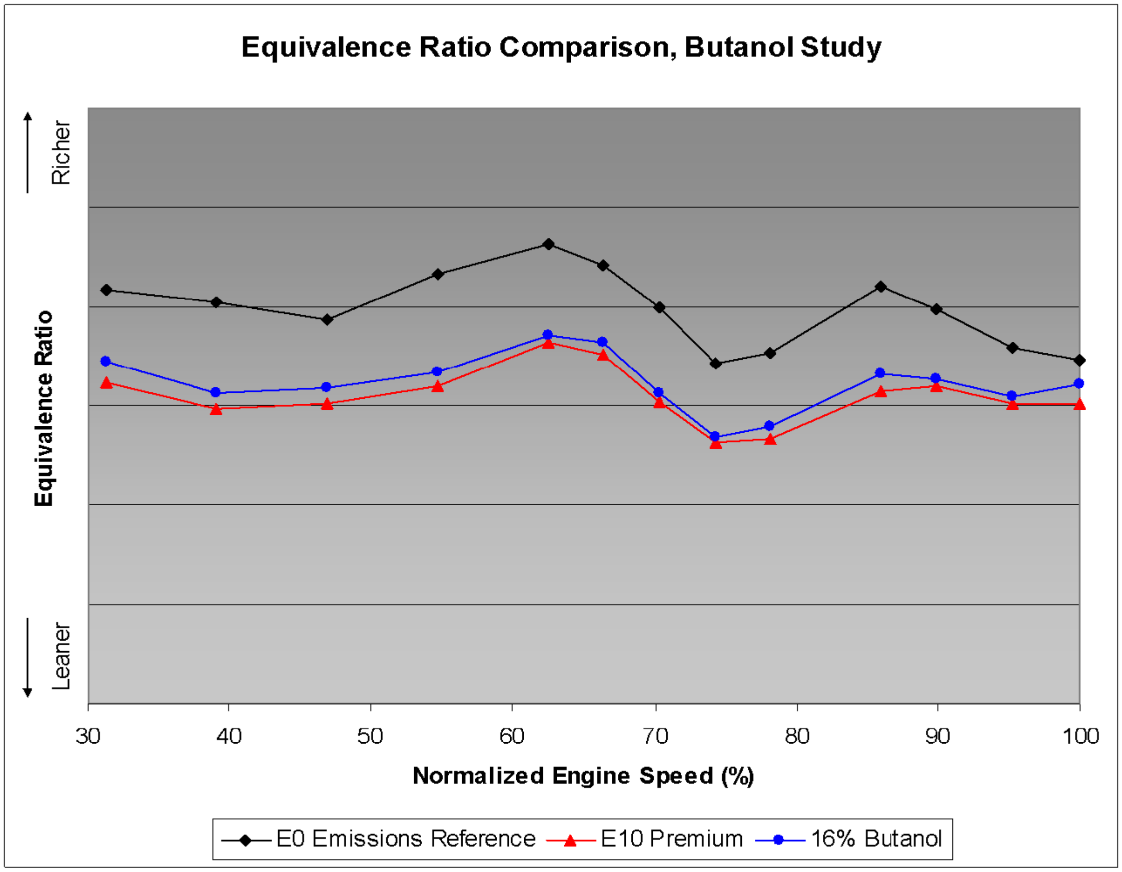

Figure 8: Equivalence Ratio Comparison

Since the engine ran leaner with Bu16 than with E0 fuel, it was expected that the exhaust gas temperature would increase, which may have valvetrain durability implications. Figure 9 shows the difference in exhaust gas temperature relative to the E0 Reference Fuel baseline. The data in Figure 9 shows that both of the alcohol blend fuels yield higher exhaust gas temperatures, with the E10 fuel running slightly hotter. The fact that the exhaust gas temperature was slightly higher when operated on the E10 fuel is expected since the engine ran slightly leaner with this fuel. The Verado engine family was qualified to tolerate E10 fuel so the exhaust gas temperature increase with Bu16 was deemed acceptable.

United States Coast Guard Isobutanol Study – Mercury Marine

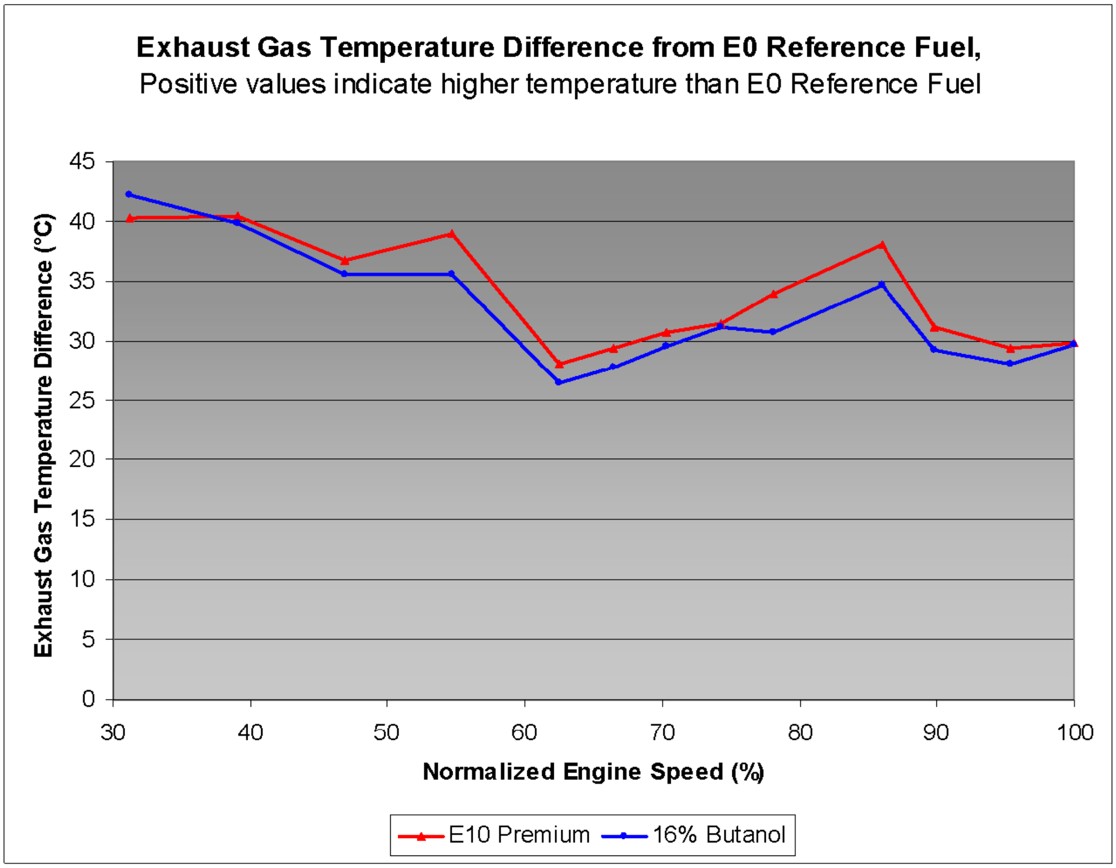

Figure 9: Exhaust Gas Temperature Comparison

The marine emissions test cycle is a 5-mode, steady-state test with Mode 1 being rated speed/full load and the subsequent mode points reducing in speed and load to Mode 5, which is idle. Figure 10 below shows the difference in emissions with the E0 Emissions Reference fuel values as the baseline. The expectation would be that an oxygenated fuel would cause the hydrocarbon (HC) and carbon monoxide (CO) emissions lower and the oxides of nitrogen (NOx) emissions higher (predominantly at high loads) on this open-loop fuel controlled engine. The butanol blend fuel has noticeably lower HC emissions than the E10 premium fuel, which was not expected purely based on equivalence ratio. The likely explanation can be understood after looking at the distillation curve in Figure 1. This blend of Bu16 that was tested is more volatile above approximately 100°C which could lead to better fuel preparation and thus lower HC emissions. The NOx emissions on the alcohol fuels are higher at the higher mode points, as expected. At the lower speed/load points, the NOx emissions are relatively low on any of the fuels. The CO emissions are lower at all mode points when the alcohol fuels are used since CO formation primarily caused by operating the engine rich of a stoichiometric mixture. At mixtures leaner than stoichiometric mixing, the engine generates very little CO (close to zero). The dramatic percentage drops in CO shown in the chart at Modes 2 and 3 are caused by the fact that the alcohol fuels cause the engine to run leaner than a stoichiometric mixture, which drives the CO to near-zero.

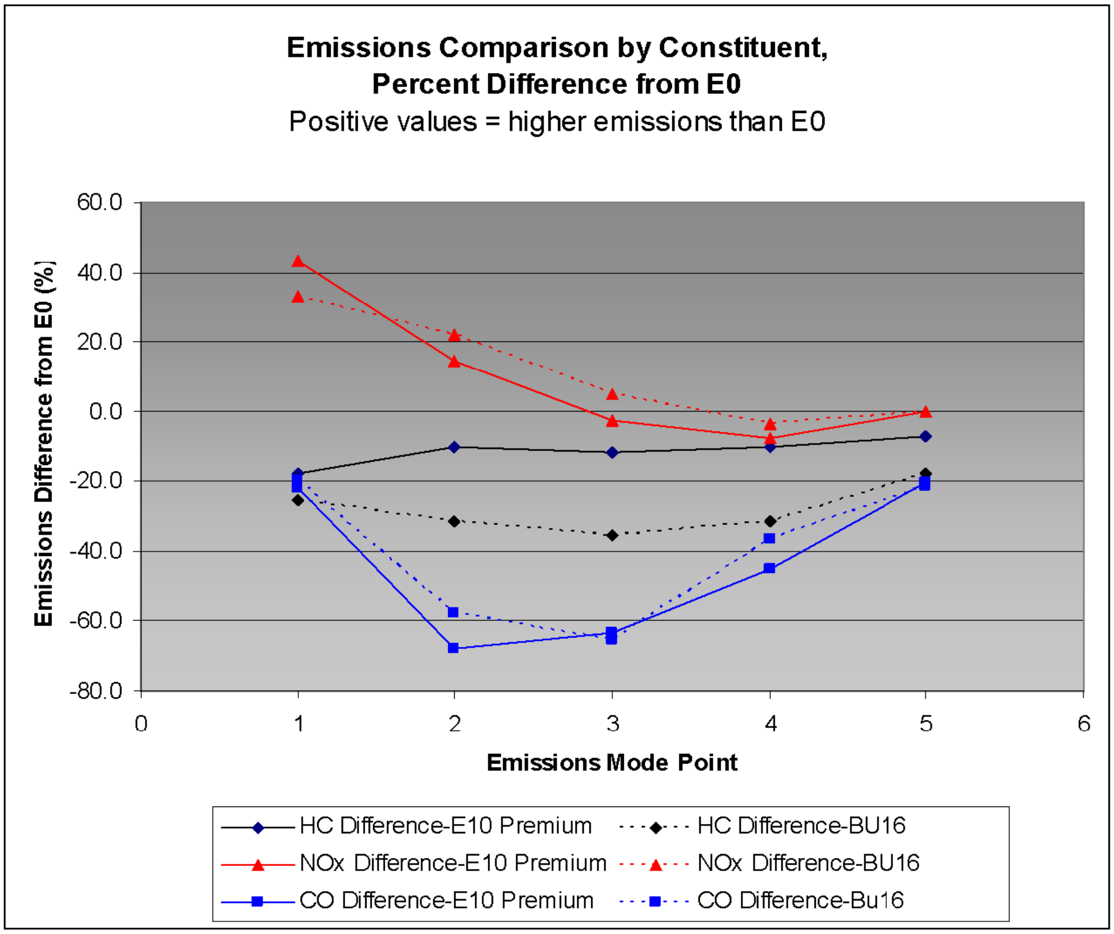

Figure 10: Emissions Comparison

Figure 11 below shows the results of the fuel in oil dilution test. In general, all 3 fuels demonstrated very low dilution rates; well below the target value. The dilution rate is likely to be more affected by the overall distillation curve shape than by the butanol itself.

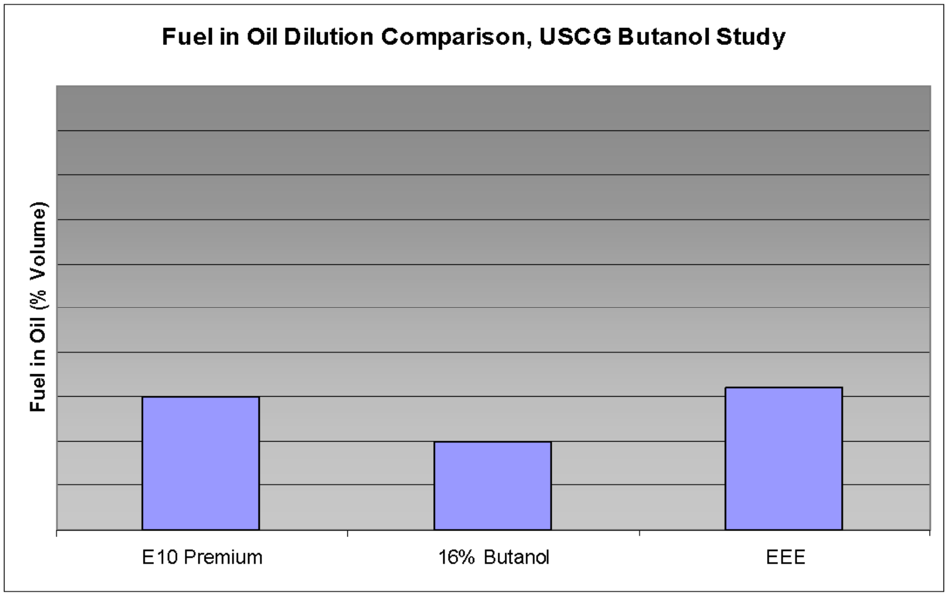

Figure 11: Oil Dilution Comparison

The knocking tendencies of the fuels were also evaluated. As the data in Table 3 above shows, the expectation was that the Bu16 fuel would be more prone to knocking, then the E0 Reference fuel, and finally the E10 premium. Even though the butanol fuel had a tendency to show knock at lower spark advance settings than the other fuels, there is still enough margin on the base calibration to allow normal operation. The data shown in Figures 7 and 8 below supported the octane test results. Figure 12 shows the amplitude or magnitude of the knock measurement from the cycle that had the highest amount of knock during the measurement period. Figure 13 shows the relative occurrence rate of knocking cycles during the measurement period. It is not believed that the butanol had any negative effect on the knocking tendency of the fuel. The Bu16 fuel was simply blended at a lower octane value. The fuel used during the USCG field test needs to be blended at the correct octane rating.

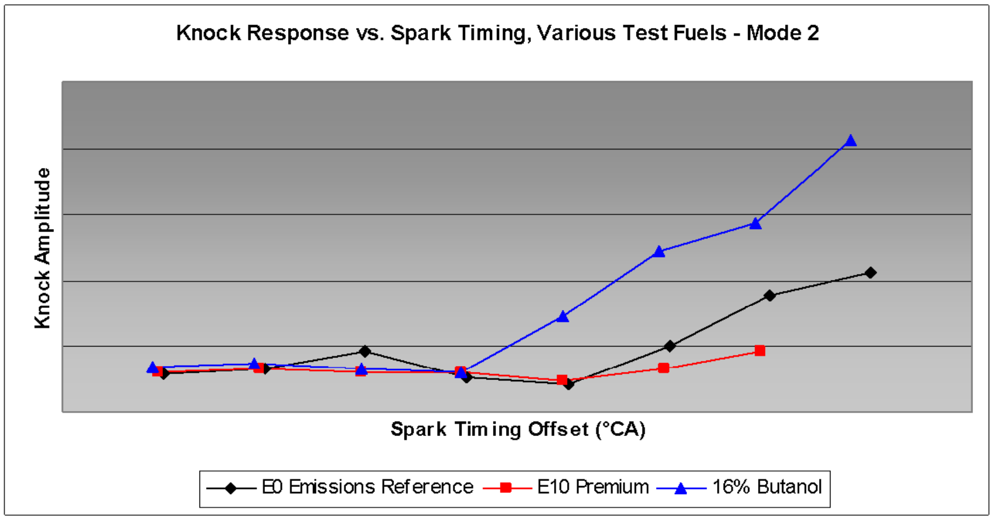

Figure 12: Knock Amplitude Measurements

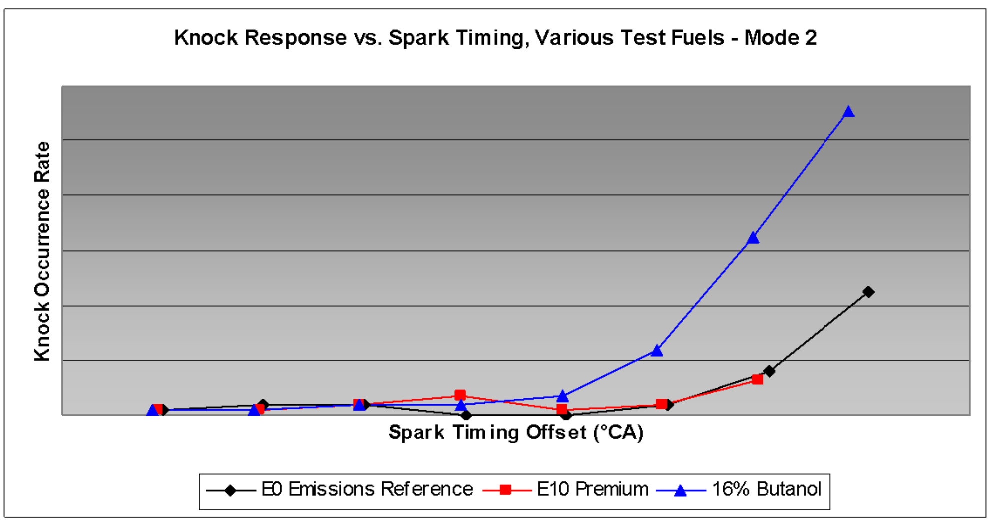

Figure 13: Knock Occurrence Rate Measurements

The final considered during the dynamometer testing was the run quality at a variety of speeds and loads through the operating region. Figures 14 and 15 shows the run quality of the engine across the operating map on Bu16 fuel and E0 Reference fuel, respectively. The run quality was evaluated based on the coefficient of variation of the indicated mean effective pressure (COV of IMEP). The data shows that the engine run quality was essentially the same on the two fuels. There were no issues uncovered in this testing.

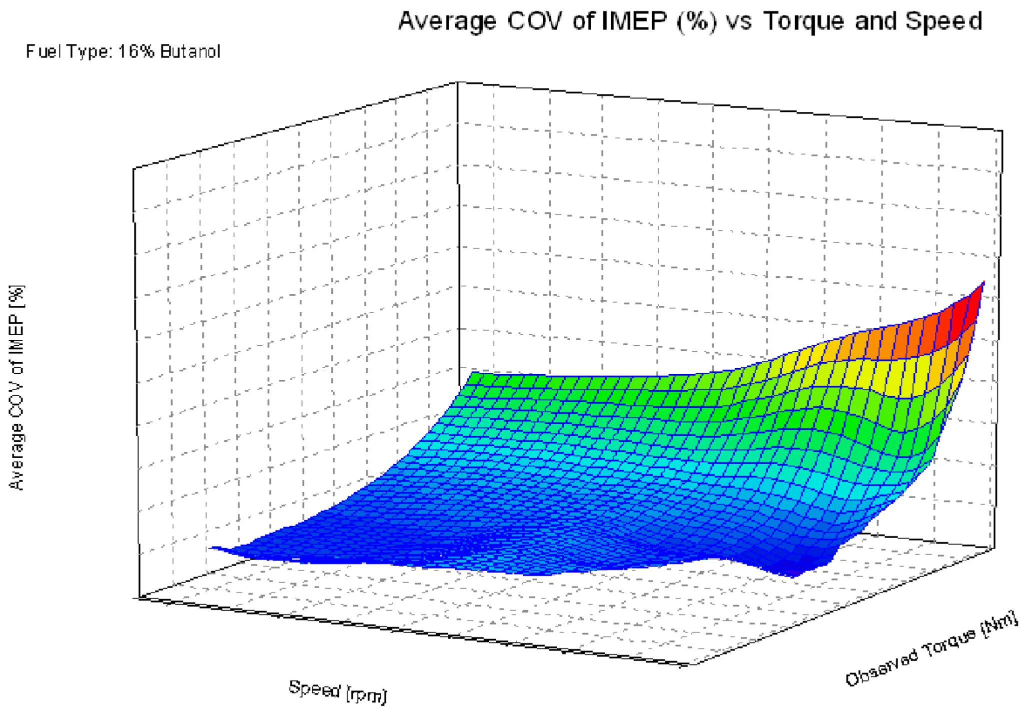

Figure 14: Run Quality Using Bu16 Fuel

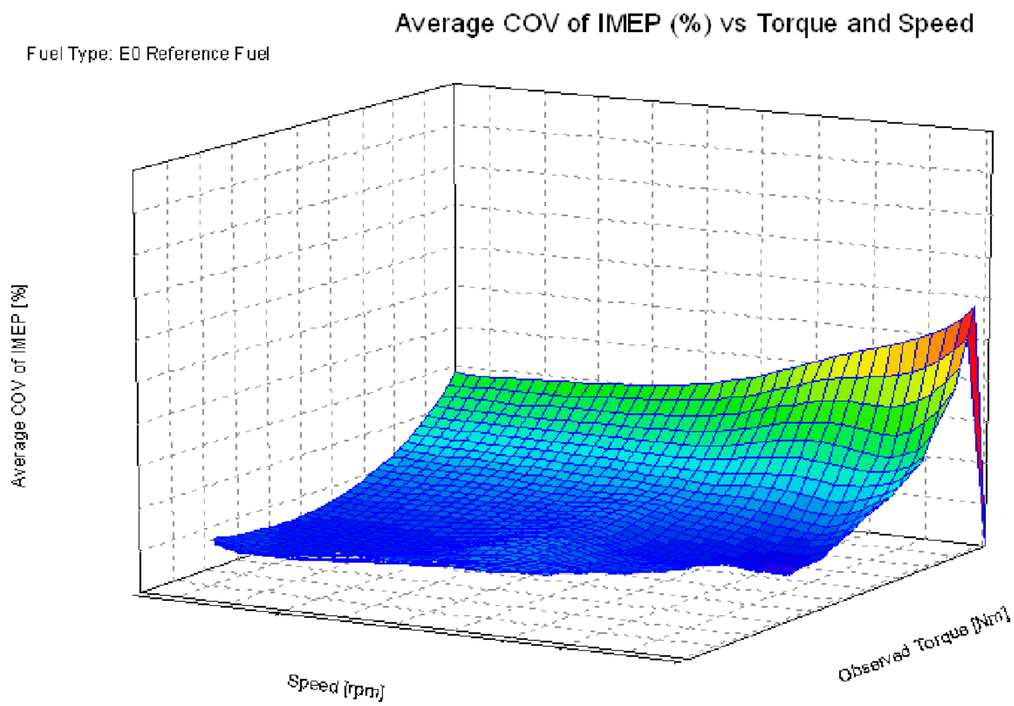

Figure 15: Run Quality Using E0 Reference Fuel

2.5.3 Calibration Driveability Evaluation:

After the dynamometer testing was completed the Bu16 fuel was evaluated for driveability considerations. The maneuvers tested were targeted at finding differences due to leaner operation on the butanol blend fuel. No significant differences were noted in the run quality when comparing the Bu16 fuel with pump-grade E0 fuel.

Data was acquired using the channels from the engine controller to allow comparison of the engine operation. Logs were taken at several steady-state conditions to allow a comparison of engine speed stability. The speed regime from idle up to 1600RPM was focused on since this is the most difficult area to achieve acceptable run quality. The results are shown in Figure 16 below. The run quality in this test was quantified by the coefficient of variation of the engine speed, which is shown as COV of RPM in the plot. The Bu16 fuel performed as good as or better than the E0 baseline fuel within the repeatability of the measurement.

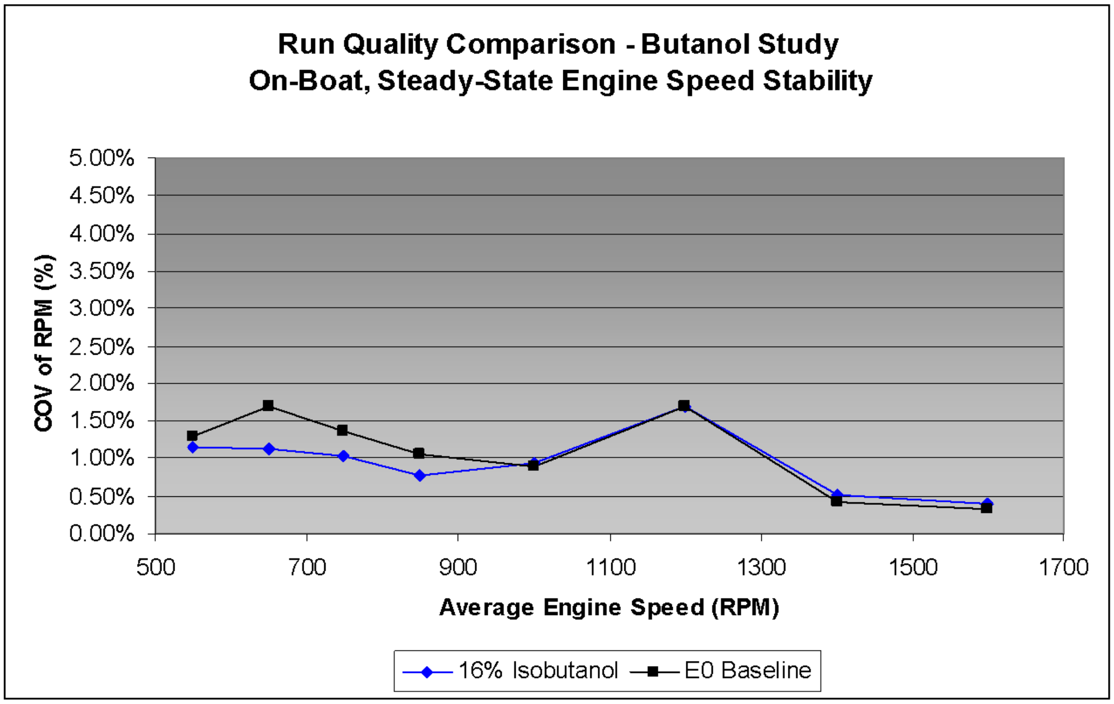

Figure 16: Engine Speed Stability Comparison, Steady-State, On-Boat

The engine operation during various transient maneuvers was also evaluated. The results from one of these tests are shown in Figure 17 below. The data shown was for a rapid acceleration which was tested in order to detect any hesitation, misfire, or other run quality issues due to lean operation. There were no issues reported on any of the maneuvers tested.

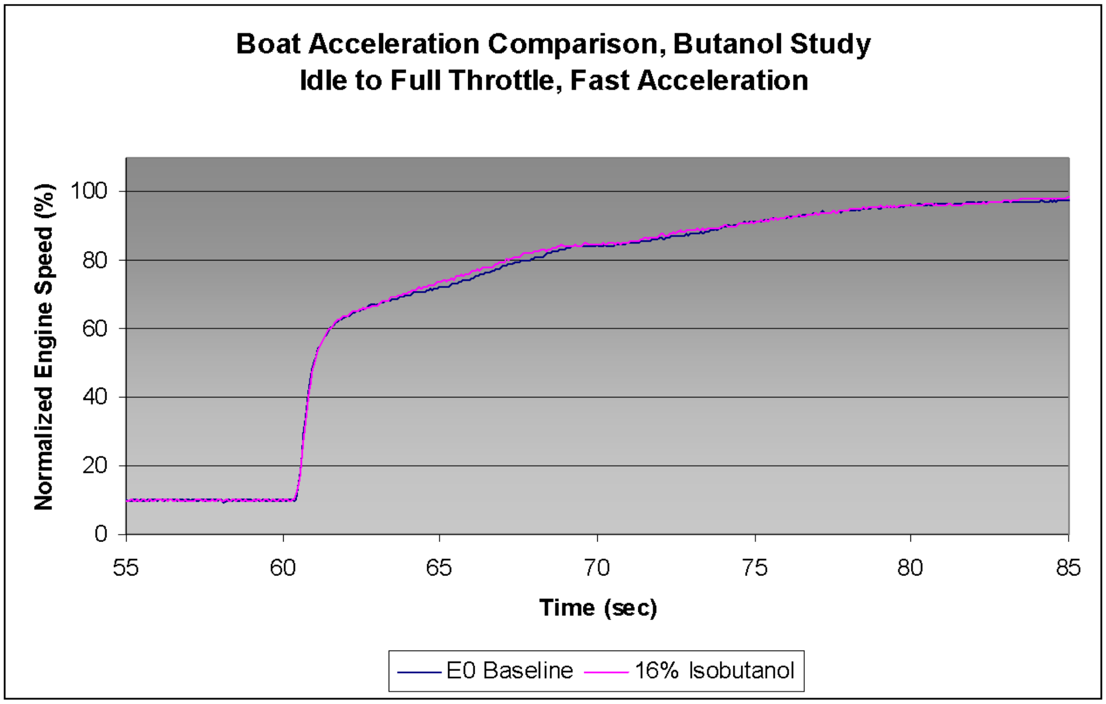

Figure 17: Rapid Acceleration Comparison

The cold starting performance was also investigated within the limits of the ambient conditions prevailing during the testing period. The logs of the engine speed during the start cycles on both fuels are shown in Figure 18 below. The log shows that the engine started slightly sooner with Bu16 fuel and as a result, did not have as much speed overshoot, and settled down to normal idle speed slightly faster than the E0 baseline fuel. The cold start performance is greatly influenced by the low temperature volatility of the fuel (RVP, etc.). The E0 baseline fuel for the driveability testing was not analyzed so the volatility comparison cannot be made for this testing. This testing showed that the starting performance on the Bu16 blend used was acceptable and no cold start issues are anticipated, assuming that the fuel used in the USCG field testing is blended appropriately for the ambient conditions.

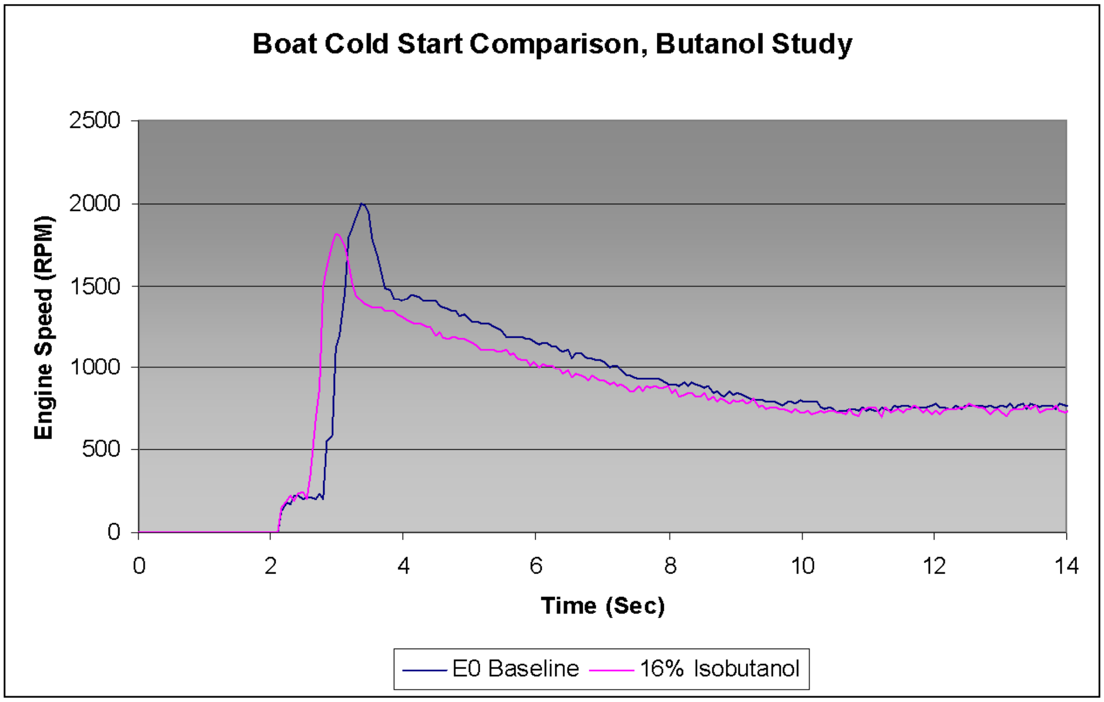

Figure 18: Cold Start Engine Speed Logs

Other maneuvers were performed and evaluated on each fuel. These maneuvers included a variety of starting and warm up tests, acceleration and deceleration tests, shifting tests, idle tests, and throttle response tests. Data logs of all of these maneuvers were not taken but the operator reported no driveability concerns with either fuel. The Verado engine has acceptable driveability performance on Bu16.

3 FINAL SUMMARY

3.1 Summary of Results:

3.1.1 Fuel System Bench Test:

The materials compatibility evaluation has shown that all performance of the components: 1. fuel water separator filter, 2. all fuel hoses, 3. fuel injectors, 4. vent canister, and 5. fuel supply module (FSM), after being tested at an elevated temperature of 60° C for a duration of 30 days have passed post-evaluation tests as defined by production specifications.

3.1.2 Dynamometer Evaluation:

The tests performed on the dynamometer did not uncover any issues while operating on Bu16 fuel. The power was slightly higher when using the 16% butanol fuel and also with the E10 pump-grade fuel. The increase in power can mostly be ascribed to higher intake air density due to evaporative cooling from the alcohol components of the fuels. The results exhibited essentially no change in observed power.

The HC and CO emission outputs were lower while operating the engine with Bu16. Since the Bu16 fuel tends to make the open-loop fuel controlled engine to run lean, the HC and CO trends are expected. Conversely, the NOx emissions increased at the high speed/load emissions test points due to the lean operation causing an increase in combustion temperatures.

The amount of fuel diluted in the oil was also quantified. There was very low fuel in oil dilution measured on all 3 test fuels evaluated in this testing.

The knock tolerance of the engine was also measured on the engine via in-cylinder pressure transducers for all 3 test fuels. The engine was driven into knocking combustion by changing the spark timing using the engine controller. The butanol blend fuel had the least margin to the knock limit but this result was not unexpected. When comparing the octane values of the three test fuels, the Bu16 fuel had the lowest octane value. Regardless, the Bu16 fuel still allowed sufficient margin to the knock limit. The fuel blended for the USCG field test needs to be the appropriate octane to ensure optimum performance.

3.1.3 Calibration Driveability Evaluation:

To ensure acceptable driveability while operating the Verado engine on Bu16 fuel, a variety of steady-state and transient maneuvers were performed on a test vessel. These maneuvers were selected to accentuate any differences in operation that could be caused by the lean operation due to the oxygenated fuel. There were no notable differences in run quality between tests comparing the Bu16 fuel and the baseline E0 gasoline.

3.2 Conclusion:

The main conclusion of this evaluation was that there were no problems or issues discovered that would prevent the USCG field test portion of the project from progressing.

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